Financing adaptation and the green transition

Climate risk, housing, and capital markets

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Financing Adaptation and the Green Transition: Climate Risk, Housing, and Capital Markets

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The chapters of this dissertation explore the macro-financial dimensions of climate change, examining how markets and financial frictions shape households' adaptive responses and investors' role in financing the transition. It shows how physical climate risks affect housing markets, highlighting how financial constraints hinder effective adaptation, reinforcing inequality and influencing political support for public intervention. On the transition side, it analyzes how capital markets price climate risk and value green innovation activity, underscoring the role of institutional investors in directing funds toward the green economy. Together, the chapters of this dissertation demonstrate how financial incentives, frictions, and political dynamics interact to shape climate resilience and the green transition.

Yasmine van der Straten studied Economics and Law at the undergraduate level, earning a BSc in Economics and a LLB in Dutch Law from Erasmus University Rotterdam. After, she completed a research master (MPhil) in Economics at the Tinbergen Institute, where she developed a strong interest in climate finance, macro-finance, and political economy. This motivated her to pursue a PhD in Finance at the University of Amsterdam, under the supervision of Enrico Perotti and Rick van der Ploeg. Currently, Yasmine is an Assistant Professor of Finance at Nova School of Business and Economics.

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877

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During his macrofinance course, I started working on what eventually became my job market paper, studying how climate change affects house prices and its redistributive effects. It took time for the paper to take shape, and along the way, others raised questions about where I was going with it. But Enrico consistently believed in the idea I was pursing and encouraged me to stay the course. This gave me the confidence to develop the paper, and once results were there, it started to gain traction – in part because of its non-conventional approach – and was selected for major conferences and

awarded best paper prizes. The project became a stepping stone of my PhD, with two papers directly building on its insights, one of which is co-authored with Enrico.

Enrico gave me the courage to pursue big questions and to let the methodology follow rather than lead – something I appreciated in him as a researcher from the start. He was always available: whether to discuss research, teaching, (academic) life, or just to exchange thoughts more broadly. I have learned so much from those meetings, as well as from Enrico actively involving me in various initiatives, such as co-organizing conferences, rethinking the structure of his course structures, and coordinating the reading group tied to his grant. I am very grateful that Enrico trusted me with these responsibilities from early on. Enrico generally valued bringing together – not just for work. He made time to go ice skating, organize drinks and dinners with all his PhD students, and – most memorably – he and **Nicky** hosted an annual Christmas party at their home. Being Enrico's PhD student was thus not only an experience I learned a great deal from, but also a very enjoyable time.

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the green paradox and discount rates. Understanding these concepts properly has been really valuable for the research I'm working on.

As Rick's primary position is in Oxford, I would only see him from time to time in Amsterdam. But every now and then we would run into each other at (environmental) economics conferences, where I would be presenting our joint paper with Enrico. Whenever Rick was around in Amsterdam, he took the time to catch up over long coffee breaks at Coffee Company or Lebkov, or lunches on the Roeterseiland Campus. While these meetings were meant to talk about our joint research, it was often a challenge to compete with Rick's enthusiasm for art, culture, fashion, politics, or many other topics. But that was part of what made these conversations so enjoyable, as I would always leave having learned something unexpected. I also had the chance to visit Rick twice in Oxford during my research visit in London, where he introduced me to several of his PhD students, colleagues, and took me to a formal Oxford college dinner – which felt like stepping into a Harry Potter movie.

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Central Bank. Getting started with empirical work, especially with a data-set like SHS, proved challenging, but I could always rely on Martijn B. having time to co-work with me and guide me through the specifics of the data, and on Maurice to help us think carefully through the empirical strategy. Working on the project with Maurice and Martijn B. allowed to grow as researcher and to appreciate more empirical work. The paper also experienced growth and became my first paper to get into a top-tier finance conference. Beyond being productive, meetings with Maurice and Martijn B. were always nice moments to catch up on research and how things going – in my PhD, at the Dutch Central Bank and in life more generally.

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List of authors

Flooded House or Underwater Mortgage? The Macrofinancial Implications of Climate Change and Adaptation
This chapter is single-authored.

The Political Economy of Climate Change Adaptation
with E. C. Perotti and F. Van der Ploeg.

Funding the Fittest? Pricing Climate Risk in the Corporate Bond Market
with M. A. Boermans and M. J. G. Bun.

Home Improvements, Wealth Inequality and the Energy Efficiency Paradox
with M. I. Dröes.

Contents

Chapter 1

Introduction

The urgency of the climate crisis continues to grow, as the physical impacts of climate change intensify and current mitigation efforts remain insufficient to keep global warming with the 1.5 – 2 degrees Celsius threshold. Weak policies create uncertainty, leaving households, firms, and investors increasingly exposed to climate-related risks. Financial markets, by their forward-looking nature, have the potential to anticipate and price these risks, thereby playing a crucial role in guiding efforts to mitigate climate change and adapt to its impacts. Accurate price signals can help reallocate resources efficiently by reflecting long-term climate risk in asset valuations. However, financial frictions may prevent price signals from adjusting appropriately, leading to mispricing of climate risk and underinvestment in resilience and decarbonization.

This dissertation examines the broader macro-financial implications of climate change, addressing two broad questions. First, I study how market incentives and financing frictions shape households' response to climate change, through adaptation and mitigation, along with the resulting distributional effects and implications for political support for climate policies. Second, I examine how investors respond to firms' efforts to mitigate climate transition risks and the associated pricing implications.

To answer these questions, I develop and analyze models that combine insights from macroeconomics, household finance, and climate finance. Across the chapters, I focus on heterogeneity in both exposure to climate risk and in capacity to respond –

either through adaptation or mitigation. I use both theoretical tools and empirical data, including household micro-data from the Netherlands, global firm-level data on emissions and (green) innovation, and confidential bond-level holdings data from European investors.

The first part of this dissertation focuses on adaptation to physical climate risk. Due to insufficient progress on mitigation, adaptation is becoming increasingly important to reduce our vulnerability to climate impacts and moderate economic losses and damages. Physical climate risks not cause large-scale damages to economic production, but also have a direct impact on real estate markets, through house prices, lending and insurance decisions. However, it remains unclear how financial incentives shape private adaptation efforts.

In the second chapter, I study the macro-financial implications of climate change and private adaptation. What is the direct effects of climate change on house prices? Do households adapt efficiently given price signals? Are there any indirect feedback effects, as financial constraints hinder those most vulnerable to reduce their exposure to climate risk? I embed climate change in a general equilibrium framework with overlapping generations. Physical climate risks damage housing and degrade land, which is in inelastic supply. Houses are traded across generations and, due to their forward-looking nature, account for climate risk. Climate change affects house prices along two channels. The exposure to future climate risk reduces demand for housing, as future damages lower the expected resale value. However, as climate change also degrades land, this increases households' marginal utility from owning housing, driving up their willingness to pay. If households are sufficiently risk averse with respect to their housing consumption, this latter effects dominates, leading to an increase in house prices in the long run.

I analyze the changing incentives of households to invest in climate change adaptation against the backdrop of rising climate risk. This choice is largely influenced by house prices, which reflect the value at risk for households. As house prices are forward-looking, prices, in equilibrium, reflect the value of an additional unit of hous-

ing for next generations. As a result, households internalize the effect of their adaptation efforts for future generations and, as long as climate risk is accurately reflected in house prices, unconstrained households adapt efficiently.

Price signals are insufficient to guide adaptation efforts in the presence of financial constraints, however. Credit constraint households have weaker incentives to adapt optimally to climate change, as they prioritize present housing consumption over investing in future climate resilience. Specifically, as credit constraints limit the extent to which households can borrow against the future, their marginal cost of adapting is effectively higher. Therefore, these households discount the benefits of adaptation to a larger extent than unconstrained households do, and end up protecting a smaller fraction of their housing wealth. Unequal adaptation reinforces wealth inequality and leads to a further reduction in future habitat. Since the underinvestment in adaptation causes credit constraints to bind even more, the private adaptation gap widens over time. Credit constraints thus form a significant obstacle to effective adaptation, making it crucial to shift the burden of adaptation investment to those with deeper pockets. I demonstrate that a societal shift from constrained homeownership to a rental model with unconstrained owners could lead to more efficient adaptation.

Economic polarization tightens financial conditions, limiting private adaptation to climate risks. Public intervention can mitigate these effects by preserving habitable land through protective infrastructure, but such investment depends crucially on political support. In the third chapter of this thesis, we analyze how political support for tax-funded public adaptation evolves over time amid rising climate risk and economic inequality. Households differ by age, income, and political beliefs – which are key factors shaping their preferences for public climate policies. Initially, political support for adaptation is low but increases as climate risk intensifies and habitable land diminishes, driving up housing prices and the value of preventive measures. This changes preferences for adaptation in an asymmetric manner across voter groups. We highlight the possibility of "political tipping", which is a shift in the political equilibrium in response to rising climate risk, leading to a more active adaptation policy.

Growing economic inequality may introduce an additional tipping point, as lower-income households stand to gain more from public adaptation. However, the policy impact depends on the balance between income differences and heterogeneous political beliefs. This highlights the importance of redistributive policies to effectively contain the damages from climate change. Overall, we show that public intervention is undermined by a "tragedy of the horizon" effect as cohorts partially internalize benefits only over the near future, limiting long-term collective action. As a result, the public response falls short of the social optimum even when political support is highest.

As the most ambitious strategies cannot fully shield our economies from climate-related losses, transiting towards a green economy is essential. The second part of this dissertation turns to the role of finance in fostering the green transition. In the fourth chapter, we study whether financial investors price climate transition risk. We focus on the corporate bond market, which is the marginal source of finance for many firms - particularly those in polluting sectors. We take a forward-looking approach and consider companies' green innovation activities, alongside their past and current carbon emissions, in the bond pricing relationship. We find a positive climate transition risk premium, which increases with the emission intensity of a company. This risk premium is significantly lower for emission-intensive firms that engage in green innovation, suggesting that investors value companies' efforts to mitigate climate change.

Using confidential bond-level holdings data, we show that the pricing of climate transition risk is driven by European institutional investors, particularly mutual funds. These investors have a higher demand for bonds from emission-intensive firms that engage in green innovation. Our evidence suggests that risk pricing is the channel through which environmental performance influences bond yield spreads, thus highlighting the importance of investors with risk-bearing capacity in reallocating capital toward firms that are currently emission-intensive but are actively investing in cleaner technologies.

The green transition also calls for households to decrease energy consumption within their homes. Building on the insights of the second chapter of this thesis, the fifth chap-

ter of this dissertation empirically investigates at the micro-level whether the pace at which households green their home is unevenly distributed across society, and what the implications thereof are for wealth inequality and aggregate emission reductions.

We use unique data from the Netherlands, combining survey data on energy efficiency enhancing home improvements, with administrative data on energy labels, income, wealth and energy expenditures. Our findings indicate that low-income households are less likely to do energy efficiency enhancing home improvements, while higher-income households are more likely to prior sort into less energy efficient homes. We estimate energy savings resulting from energy efficiency enhancements and show that sorting explains the majority of those. Savings are relatively larger for low-income households. While this calls for policies encouraging energy-efficiency enhancements by low-income households, we show that this would miss the majority of potential emission reductions, as higher-income households have higher carbon footprints. Our results thus brings forward a policy trade-off between reducing wealth inequality and effectively reducing emissions.

Taken together, the chapters in this dissertation highlight the importance of incorporating heterogeneity in exposure to climate risk and in the ability to respond across households, firms, and investors. The analyses show how financial constraints shape households' private adaptation and mitigation choices, how political support for climate policy evolves with exposure, and how investor demand can reallocate capital in response to climate transition risk and green innovation. By combining theoretical models and empirical data, this dissertation contributes to a more detailed understanding of the resulting distributional and efficiency implications of climate responses.

Chapter 2

Flooded House or Underwater Mortgage? The Macrofinancial Implications of Climate Change and Adaptation [1]

Abstract

This chapter studies the macrofinancial implications of climate change on housing markets and private adaptation efforts. Households are exposed to physical climate risks, damaging housing and degrading land which is in inelastic supply. While the exposure to climate risk weakens demand for housing, I show that the materialization of climate change raises house prices, as habitat becomes increasingly scarcer. This leads to a reallocation of credit in the economy towards households. In frictionless markets, price signals lead to efficient adaptation. However, credit-constrained households have weaker incentives to adapt to climate change, indicating that pricing alone may be insufficient. Unequal adaptation reinforces wealth inequality and leads to a further reduction in future habitat. As housing becomes increasingly important relative to future consumption, the private adaptation gap widens over time. I show that a societal shift from constrained homeownership to a rental model with unconstrained owners could lead to more efficient adaptation.

Keywords: Climate Change, Adaptation, Housing, Financial Constraints, Flood Risk, Wealth Inequality.

JEL codes: E44, G51, Q54.

[1] This chapter is based on Van der Straten, Y. (2023). Flooded House or Underwater Mortgage? The Macrofinancial Implications of Climate Change and Adaptation. Tinbergen Institute Discussion Paper No. TI 2023-014/IV.

2.1 Introduction

The urgency of climate change adaptation is becoming increasingly evident as climatic impacts intensify across the globe, and mitigation efforts remain inadequate in preventing temperatures from rising by more than 1.5-2 degree Celsius (UNEP, 2023). This raises the question how to address rising physical climate risks. While mitigation efforts seek to prevent further climate change by limiting global emissions, adaptation measures are implemented to reduce our vulnerability to existing climate impacts, moderating potential economic losses and damages (IPCC, 2021). A growing macro-literature studies whether we are adapting to climate change and what the welfare consequences thereof are (see e.g. Burke, Zahid, Martins, Callahan, Lee, Avirmed, Heft-Neal, Kiang, Hsiang, and Lobell, 2024; Bilal and Rossi-Hansberg, 2023; Hong, Wang, and Yang, 2023; Fried, 2022), yet the role of finance remains underexplored. Physical climate risks may lead to significant economic losses (see e.g. Barrage and Nordhaus, 2024; Bilal and Känzig, 2024), but also directly impact real estate markets. A substantial finance literature investigates whether physical climate risks are priced into house values and whether they are factored into lending and insurance decisions (see e.g. Bernstein, Gustafson, and Lewis, 2019; Baldauf, Garlappi, and Yannelis, 2020; Bakkensen and Barrage, 2021; Sastry, Forthcoming; Ge, Lam, and Lewis, 2022). However, it remains unclear how those market incentives, and potential financing frictions, shape private adaptation efforts.

In this paper, I study the implications of climate change on housing markets, mortgage credit, and private adaptation. What is the direct effect of climate change on house prices? Do households adapt efficiently given price signals? Are there any indirect feedback effects, as financial constraints prevent the most vulnerable households from reducing their exposure to climate risk, as access to credit crucially determines our ability to adapt? I take a long-term perspective and embed climate change in a general equilibrium framework with overlapping generations. Floods occur in each period, damaging housing and degrading land. Houses are traded across generations, and house

prices account for climate risk due to the forward-looking nature. I show that climate change affects house prices along two channels. First, the exposure to future climate risk reduces demand for housing, as future damages lower the expected resale value. However, as flooding events also degrade land, this reduces its long term usability and diminishes the housing supply over time. This scarcity effect puts upward pressure on house prices, and dominates in the general equilibrium if households are sufficiently risk averse with respect to their housing consumption, leading to an increase in house prices. I endogenize households' choice to invest in protective measures to adapt to climate change. Their private adaptation choice is largely influenced by house prices, as it reflects the value at risk to households. Since house prices are forward-looking, they incentivize households to internalize the benefits of their adaptation investments for future generations. Thus, in frictionless markets, price signals support efficient adaptation. Pricing is insufficient, however, if households are financially constrained. This is because financially constrained households optimally prefer to allocate a larger share of their constrained budget on housing consumption in the present rather than on investing into future resilience. As a consequence, financially constrained households protect a smaller fraction of their housing wealth. This underinvestment reinforces wealth inequality. It also increases the rate at which land degrades, which causes households to become endogenously more constrained. Over time, the difference between the constrained and unconstrained choice of adaptation (i.e., the "adaptation gap") rises. I propose that a shift from a model of constrained homeownership to a rental model with unconstrained owners can lead to more efficient adaptation. Through the reassignment of ownership in a rental model, landlords bear the responsibility for undertaking adaptation investments. Since adaptation increases the resale value of housing, rental prices in a perfectly competitive market provide a signal that incentivizes landlords – as the residual claimants – to invest optimally in resilience. Unlike constrained homeowners, landlords therefore have both the financial means and the long-term incentive to internalize the benefits of adaptation.

I build a simple model of housing and climate risk. The economy is populated by

households, who live for two periods. Households have heterogeneous (and exogenous) skills, which determine household income, being either of the high-income or the low-income type. Households have preferences over a non-durable consumption good, which households consume when they are old, and housing, which they consume when they are young. Houses are traded across generations, with the young purchasing the the stock of houses from the old in each period. Housing is a risky investment, as the economy is exposed to physical climate risks.[2] Floods occur in each period and, with a certain probability, households experience losses due to the flood. All risk is thus idiosyncratic of nature. Floods not only destroy part of the housing stock, but also degrade land. Land degradation occurs over a quarter of the earth's ice-free land area. Climate change accelerates the rate and scale of ongoing land degradation processes and generates new degradation patterns. For example, climate change intensifies land degradation through increased flooding, erosion, land subsidence and soil salinity, landslides, and rising sea levels which accelerates coastal erosion worldwide (IPCC, 2019).[3] Such degradation processes can render previously habitable land unsuitable for (re-)development, adversely affecting its long-term usability. Within coastal areas, land is often in inelastic supply due to geographic constraints (Saiz, 2010). As a result, land degradation processes render habitable land increasingly scarce.

Since houses are traded across generations, house prices are forward-looking and reflect the physical risks it is being exposed to. In equilibrium, climate change affects house prices along two opposing channels. First, the exposure to physical climate risk weakens demand for housing, as future damages lower the expected resale value of housing. The future resale value of the house is thus discounted for the exposure to climate risk, which lowers current house prices (see e.g., Bernstein et al., 2019; Bosker,

[2] I focus on the risk of flooding from extreme weather events (e.g., pluvial floods, hurricanes and torrential rains) and rising sea levels. However, other physical climate events, such as wildfires, would generate similar effects.

[3] I focus on the case in which the change in land supply due to climate change is net negative, which is empirically most relevant. Already at present, soil is being lost from land that is tilled at a rate more than 100 times faster than new soil is naturally being formed. Moreover, due to climate change, erosion of coastal areas will increase worldwide, even with adequate implementation of measures to avoid, reduce and reverse land degradation (IPCC, 2019).

Garretsen, Marlet, and van Woerkens, 2019; Baldauf et al., 2020). However, due to the degradation of land, habitable land becomes increasingly scarcer, leaving less housing available in the economy over time.[4] The reduction in supply puts upwards pressure on house prices. If households are sufficiently risk-averse with respect to their housing consumption, this scarcity effect dominates, causing house prices to rise in the long run equilibrium.

I introduce private adaptation to climate change by allowing households to invest in self-protective measures that reduce their vulnerability to floods. There is a growing need for private adaptation to complement public adaptation investments. Individuals often have a better understanding of the specific risks and vulnerabilities they face and, unlike broad public policies, private adaptation measures can be tailored to their individual risk exposure and preferences. Moreover, as public adaptation investments require political support, private adaptation allows for a quicker responses to local risks when public investments either are insufficient or slow to implement. I model private adaptation investments as an intertemporal investment that households can undertake.[5] Private adaptation measures, such as storm-proof windows, or flood-proof floors, do not change the probability of a flooding event occurring or the progression of climate risk, but reduce the damages households experience when hit by a flooding event. That is, adaptation investments shift the distribution of idiosyncratic damages leftwards. As a result, private adaptation investments also directly influence the speed at which the housing supply diminishes, as these measures can mitigate the impact of flooding, thereby slowing the rate of land degradation.

Adaptation investments are costly, however, and households trade off the present costs and future benefits of adaptation in the form of avoided climate change damage.

[4] As land degrades, rebuilding housing in the affected part of the region becomes prohibitively costly. While new homes could be constructed in unaffected parts of the regions, a similar amount of households must share a smaller amount of land. The supply reduction can also be interpreted as regulatory restrictions on development in flood-prone zones.

[5] While I focus on private adaptation by households aimed at protecting the housing stock, the model set-up is general, and can therefore be interpreted more broadly to reflect adaptation by farmers to prevent a loss in the productivity of their agricultural land, or investments in public adaptation infrastructure by local municipalities.

The private adaptation choice increases in the economy's climate risk exposure, as it determines the size of the damages households can expect to face. It also rises with the house price, as it reflects the value at risk to households. Since house prices are forward-looking, they incentivize households to internalize the benefits of their adaptation investments for future generations. In other words, as a decentralized information system, prices guide the optimal adaptation decision, reflecting the expected future benefits of reducing flood risk and maintaining the long-term value of housing. This prevents a "tragedy of the horizon" effect (Carney, 2015), and leads to efficient private adaptation in frictionless markets.

There are two caveats to this result. First, to guide households to invest optimally in adaptation, price signals must be correct. That is, climate risk must be accurately capitalized into house prices. If climate risk is mispriced — due to heterogeneity in beliefs about climate change (see e.g., Bakkensen and Barrage, 2021; Baldauf et al., 2020) or limited buyer sophistication (see e.g., Bernstein et al., 2019) — households underinvest in adaptation and remain vulnerable to climate impacts. Therefore, accurate climate risk pricing in housing markets is essential for incentivizing optimal adaptation. Second, the private optimum only coincides with the social optimum if market signals accurately reflect the social benefits of a having an additional unit of housing available for the next generation. This essentially requires the welfare of future generations to be evaluated using markets discount rates Stern (2007); Nordhaus (2007); Weitzman (2007). If greater social weight was placed on the welfare of future generations, market prices would fail to reflect the value of adaptation investments to future generations and households again underinvest in adaptation from a social perspective. While determining the appropriate discount rate for mitigation efforts – which aim to protect the global climate – can be complex (Heal and Millner, 2014), adaptation is fundamentally different. Unlike the global climate, which is a public good that is not traded in the market, housing, a private and tradable asset. Since private adaptation directly protects these market-valued assets, market signals can provide guidance for adaptation investments, even if they do not fully account for broader social welfare considerations.

In times of rising wealth inequality (Saez and Zucman, 2016; Zucman, 2019; Blanchet and Martínez-Toledano, 2023), it is essential to understand the heterogeneity in households' ability to respond to rising climate risk. In the framework, households with positive savings lend to others that are unable to finance the purchase of housing from their income. Housing is pledged as collateral under the mortgage contract, but its liquidation value is affected by climate change. Mortgage creditors anticipate these potential losses and adjust their lending decisions. While borrowers can protect the liquidation value of the collateral by adapting to climate change, their adaptation investment is non-verifiable to mortgage creditors.[6] Mortgage creditors thus form expectations about the private adaptation choice of their borrowers and rationally do not allow the size of household debt to exceed the expected liquidation value of collateral (Kiyotaki and Moore, 1997; Sastry, Forthcoming).

The ability of low-income households to adapt to climate change critically depend on their access to finance. Due to binding credit constraints, constrained households are unable to consume the optimal amount of housing. This has implications for their adaptation decision, as the marginal utility from spending an additional unit on housing – from which households derive utility in the present – is higher than the marginal utility from spending an additional unit on adaptation – being an investment in future resilience. In essence, credit constrained households discount the benefits of future adaptation more heavily due to their limited ability to borrow against the future. As a result, credit constrained households optimally spend a relatively lower share of their resources on adaptation, thereby protecting a smaller fraction of their housing wealth. This has redistributive implications, since credit constrained households retain a relatively higher exposure to floods and face a relatively larger reduction in their housing wealth once the flood occurs. The underinvestment also creates intergenerational spillovers. Due to the underinvestment in adaptation, the economy faces larger climate-related damages, increasing the speed of land degradation. This increases housing scarcity, reducing welfare of future generations. Moreover, the further

[6] Even if creditors could, it is nearly impossible to verify that adaptation measures are maintained and remain functional at the time of the flood.

reduction in habitat endogenously tightens credit constraints for future generations. Over time, credit constrained households thus have increasingly lower incentives to invest in resilience, widening the private adaptation gap.

Credit constraints present a significant barrier to effective climate adaptation (IPCC, 2023; Havlinova, Heerma van Voss, Zhang, Van der Molen, and Caloia, 2022), highlighting the need for targeted policies to address the unequal impacts of climate change. One such policy is to promote renting over homeownership for credit-constrained households. Through the reassignment of ownership in a rental model, landlords, rather than homeowners, bear the responsibility for undertaking adaptation investments. Rental prices in a perfectly competitive markets adjust to reflect the rising scarcity of housing due to climate change. Since adaptation increases the resale value of housing in the future, these equilibrium price adjustment incentivize adaptation investments by landlords. Landlords thus have the financial capacity and the long-term incentive to invest efficiently in adaptation.[7] In essence, renting functions as an equity-like arrangement where landlords bear the investment cost and capture the returns through higher rental income and preserved resale value. Rental markets can thus support more efficient adaptation than mortgage markets, where adaptation is hindered by collateral limits.

I quantify the welfare effects of the underinvestment in adaptation over time, focusing on the Florida coastal area. Florida is at high risk of flooding due to sea level rise, and is projected to account for more than 40 percent of all houses at risk of flooding through sea-level rise in the United States as a whole (Dahl, Cleetus, Spanger-Siegfried, Udvardy, Caldas, and Worth, 2018). I provide a long-run simulation of the model under various climate change scenarios of projected socioeconomic global changes up to the year 2150 based on IPCC (2023). Depending on the severity of the climate change scenario, the difference between the private adaptation choice of credit constrained and unconstrained households grows to 5-20 percent. Essentially, this represents the difference in the housing wealth that credit constrained households relative to unconstrained households. While this has implications for wealth inequality – as constrained house-

[7] The rental model also overcomes the information problem posed by non-verifiable adaptation investments, as prices reflect the underlying value of the adaptation measures.

holds lose a relatively larger fraction of their housing wealth upon the realization of a climate impact –, it also has implications for welfare more broadly.

Under the most extreme climate change scenario, the marginal value of housing saved through adaptation rises to up to 11.7 percent of a household's consumption – reflecting the amount a household is willing to pay to preserve an additional unit of housing through adaptation. To quantify the inefficiency caused by credit constraints, I determine the utility cost of the underinvestment in adaptation. This loss amounts to up to 3.5 percent of the home's market value, or approximately $15,700 per household. These findings highlight the long-term implications of constrained adaptation and signal the benefits of improving access to finance or shifting toward landlord-driven adaptation.

I provide a model extension in which I introduce an insurance market. Adaptation fundamentally differs from insurance, since adaptation aims at prevention, whereas insurance offers monetary compensation after losses occur. Hence, insurance does not moderate the reduction in the supply of houses. Rather, I show that insurance leads to moral hazard in adaptation (Fried, 2022). Even when priced actuarially fair, insurance allows households to limit the downside from a disaster in a way which is relatively cheaper than investing in adaptation, thus reducing households' willingness to undertake adaptation investments. Due to the moral hazard in adaptation, the reduction in the supply of habitat accelerates, leading to a more rapid rise in house prices – and thus the value of the good that adaptation aims to protect (Mayers and Smith Jr, 1983). By increasing the value at risk to households, this home equity effect provides a countervailing force. Nevertheless, it never dominates in equilibrium. Private climate risk insurance thus crowds out private adaptation. This increases inequality across generations. However, a trade-off emerges since a higher insurance coverage reduces the redistributive effects of climate change within generations due to the monetary compensation provided for damages. This underscores the relevance of considering distributional consequences in designing effective climate risk insurance schemes.

Roadmap The remainder of this paper is structured as follows. I discuss the re-

lated literature in Section II. In Section III, I introduce the theoretical framework with housing and climate risk. The conditions relevant for the definition of an equilibrium are derived in Section IV. I endogenous climate change adaptation in Section V. Section VI quantitatively assesses the welfare implications over time. In Section VII, I provide a model extension with climate risk insurance provision. Section VIII concludes.

2.2 Related literature

This paper relates broadly to the literature studying the effects of climate change. This literature can be divided into a stream focusing on quantifying the effect of a rise in temperatures on productivity, for example in agriculture, labour productivity or GDP growth more broadly (see e.g. Nordhaus, 1992, 1977; Mendelsohn, Nordhaus, and Shaw, 1994; Deschênes and Greenstone, 2007; Schlenker and Roberts, 2009; Dell, Jones, and Olken, 2012; Golosov, Hassler, Krusell, and Tsyvinski, 2014; Burke, Hsiang, and Miguel, 2015; Barrage and Nordhaus, 2024; Cruz and Rossi-Hansberg, 2024; Bilal and Känzig, 2024) and a stream of literature studying the effect of sea level rise on real estate markets, which encompasses the pricing of physical climate risk in housing markets, and the effects of physical climate risk on mortgage - and insurance markets.

This paper contributes to this latter stream, particularly to the literature studying the pricing of physical climate risk in housing markets. These papers study empirically whether sea level rise risk is capitalized into housing markets in coastal areas. The majority of papers find evidence of a positive 'sea level rise discount', indicating that houses exposed to sea level rise risk trade at a lower price in the market (see e.g., Harrison, T. Smersh, and Schwartz, 2001; Bin, Kruse, and Landry, 2008; Keenan, Hill, and Gumber, 2018; Gibson, Mullins, and Hill, 2017; Bosker et al., 2019; Bernstein et al., 2019; Hino and Burke, 2020; Keys and Mulder, 2020; Baldauf et al., 2020; Giglio, Maggiori, Rao, Stroebel, and Weber, 2021; Bakkensen and Barrage, 2021). This literature finds that factors as - amongst others - buyers' sophistication (Bernstein et al., 2019) and (heterogeneity in) climate change beliefs can explain (Baldauf et al., 2020; Murfin and Spiegel,

2020; Bakkensen and Barrage, 2021) variation in the sea level rise discount.Consistent with the aforementioned research, I show that demand for houses exposed to future climate risk is lower, which puts downwards pressure on current house prices. I contribute to the literature by considering the aggregate effect of climate change on house prices through rising scarcity. Specifically, I demonstrate that the materialization of climate-related damages reduces the supply of habitable houses. I derive the conditions under which this scarcity effect dominates in the general equilibrium, showing that this is the case when households are sufficiently risk-averse with respect to their housing consumption.

The evolution of house prices matters for mortgage market dynamics. Hence, there is a growing literature studying the effect of physical climate risk on mortgage markets. Issler, Stanton, Vergara-Alert, and Wallace (2019) show that mortgage delinquency and foreclosure rates significantly increase after a wildfire. Bakkensen, Phan, and Wong (2022) find that homeowners with a larger exposure to SLR-risk are more likely to be leveraged due to heterogeneity in beliefs about climate risk. Bakkensen et al. (2022) further find that the underlying mortgage contracts have a longer maturity, and climate change pessimists are more likely to trade their climate risk exposure with banks via long-term debt contracts. Sastry (Forthcoming) shows that mortgage originators further offload flood risk to the government through flood insurance contracts, and to under-insured households through higher down payments. This indicates that mortgage originators only screen for flood risk when they retain residual exposures to it. Building on this latter result, I consider endogenous credit constraints in my theoretical framework. Specifically, mortgage originators take into consideration the exposure to climate risk, as this reduces the expected liquidation value of collateral pledged to the mortgage contract (cf. Kiyotaki and Moore, 1997). While this reduces financial risks, I show that such credit constraints fundamentally hinder homeowners from optimally investing in adaptation.

As physical climate risk rises, so do the costs of insuring oneself against these risks. Keys and Mulder (2024) document that insurance premia have risen sharply due to

an increase in local disaster risk and the pass-through of reinsurance costs. Ge et al. (2022) show that higher insurance premia reduce transaction prices, with the effect being strongest for homes exposed to long-term sea level rise. Ge et al. (2022) suggest that insurance pricing can accelerate the incorporation of climate risk into asset markets. Boomhower, Fowlie, Gellman, and Plantinga (2024) document that high exposure to wildfire risk not only leads to higher prices, but also to limited participation in insurance markets. Sastry, Sen, and Tenekedjieva (2023) also find that traditional insurers increasingly exit the Florida-market. Importantly, Sastry et al. (2023) find that lower quality insurers enter the market to fill this gap. Mortgage lenders respond to the decline in insurance quality by selling a large portion of exposed loans to government sponsored enterprises, who bear an increasing share of insurance counterparty risk. While it is essential to ensure that premia accurately reflect climate risk exposures, I show that climate risk insurance leads to moral hazard in adaptation, even if insurance premia reflect the accurate climate risk exposure. This is because insurance limits the downside from a disaster in a way which is relatively cheaper than investing in adaptation, reducing households' willingness to undertake those investments.[8]

It is essential to consider adaptation when quantifying climate-related losses and their impact. Hence, a growing macro-literature studies adaptation to climate change. Bradt and Aldy (2023) and Hsiao (2023) focus on public adaptation. Bradt and Aldy (2023) estimate the magnitude and distribution of benefits from public adaptation infrastructure. Hsiao (2023) shows that public adaptation intervention hinders long-run resilience against flood risk by creating coastal moral hazard, which leads to lock-in and delays inland migration. Since public adaptation relies on collective efforts which require political support, and individuals typically have a better understanding of the unique risks and vulnerabilities they face, there is a growing need for private adaptation. Specifically, private adaptation measures can be tailored to meet the specific needs of individuals, which may not be adequately addressed by public policies. Fried (2022) develops a macro heterogeneous-agent model to quantify the interactions be-

[8] This is consistent with Fried (2022), who studies the effect of disaster relief policies on adaptation incentives.

tween adaptation, federal disaster policy, and climate change. Fried (2022) shows that moral hazard effects from disaster aid reduce adaptation in the U.S. economy, but federal subsidies for investment in adaptation more than correct for the moral hazard. Hong et al. (2023) analyze how private and public sectors should adapt to manage disaster risks to the capital stock when they learn about the adverse consequences of global warming for disaster arrivals. Hong et al. (2023) highlight that adaptation is more valuable under learning. In a similar spirit, Balboni, Boehm, and Waseem (2023) show that climate change impacts will be moderated as flood-affected firms in Pakistan learn from the experience of increasingly frequent disasters and increasingly relocate to safer areas.[9] However, Albert, Bustos, and Ponticelli (2021) show that spatial capital and labour market frictions constrain the reallocation process of capital and labour from agriculture to manufacturing in Brazil.

This paper contributes to the literature on climate change adaptation by taking into consideration the role of financial markets in driving private adaptation decisions. I show that the capitalization of climate risk in house prices influences the incentives of households to adapt to climate change. Specifically, in frictionless markets, price signals lead to efficient adaptation, as household internalize the effect of their adaptation investments on future generations. However, I show that pricing may not always be sufficient, as households may not have sufficient means to adapt to optimally to climate change. Indeed, credit-constrained households optimally underinvest in climate change adaption.[10] I highlight the dynamic feedback effect of credit constraints in the context of climate change adaptation. Specifically, credit constraint households remain more exposed to climate risks due to the underinvestment in adaptation. Upon an impact, their underinvestment reinforces wealth inequality. It also leads to a further

[9] I abstract from migration as adaptation mechanism in this paper. Cruz and Rossi-Hansberg (2024); Bilal and Rossi-Hansberg (2023); Desmet and Rossi-Hansberg (2015); Muis, Güneralp, Jongman, Aerts, and Ward (2015) the adaptation incentives in dynamic spatial models. For example, Cruz and Rossi-Hansberg (2024) examine responses to local temperature changes through costly trade, migration, and technological innovations, while Bilal and Rossi-Hansberg (2023) focus on migration and capital investment decisions. These papers highlight that migration may reduce substantially the welfare impact of climate change.

[10] This aligns with the findings of Rampini and Viswanathan (2013); Rampini (2019), who show that firms facing financing constraints are less likely to invest in durable assets.

reduction in future habitat. As habitat becomes increasingly scarcer in supply, next generations become more constrained and therefore underinvest to an even larger extent. This leads to a widening of the private adaptation gap over time. I propose that a societal shift from constrained homeownership to a rental model with unconstrained owners could overcome the dynamic underinvestment problem and lead to more efficient adaptation.

Finally, this paper relates to the literature studying the effects to climate change policies on inequality. Känzig (2023) shows that a carbon taxes disproportionately affects the poor, as these households have a high energy share within their consumption bundle, and tend to work in sectors which are more impacted by carbon pricing policies. Pedroni, Douenne, and Hummel (2022), Belfiori and Macera (2024) and Belfiori, Carroll, and Hur (2024) study how inequality can be optimally accounted for in climate mitigation policies.

2.3 A Simple Framework of Housing and Climate Risk

Time is discrete and denoted by $t \in \{0, 1, ..., \infty\}$. The economy is characterized by two overlapping generations, each consisting of a unit mass of households. Households derive utility from consuming housing and a non-durable consumption good, which is in infinite supply (in Section VI, I introduce firms which produce this good). At the start of each period, a flood occurs. This event hits a fraction of households, damaging their housing capital. All risk is idiosyncratic, and the economy's climate risk exposure rises deterministically over time.

2.3.1 Households

Households live for two periods. When young, households purchase housing capital, denoted by L, from the old generation at a relative price p (the price of the consumption

good is normalized to 1).[11] Additionally, young households hold financial assets, and can invest in mortgage debt. Once old, households channel their savings, which consist of the proceeds from selling their house, as well as the return earned on their savings, to the purchase of the non-durable consumption good, denoted by c. There is an initial generation at $t = 0$, which is endowed with the supply of houses, $\bar{L}_0$.

Preferences

Households have preferences over housing and the non-durable consumption good[12], which are given by the following quasi-linear utility function

$$U\left(c_{i,t+1}, L_{i,t}\right) = c_{i,t+1} + v\left(L_{i,t}\right)$$

$v\left(L_{i,t}\right)$ captures the utility that household i obtains in period t from owning $L_{i,t}$ housing capital. I assume that $v'(\cdot) > 0, v''(\cdot) < 0$. Households maximize expected lifetime utility.

Skills and Wages

Households have heterogeneous (and exogenous) skills, which determine household income. There are two skill levels. I denote high skills and income by h and low skills and income by l. A fraction ϕ of households is high-skilled, and is endowed with $\bar{h}$ high-skilled labour. The remaining households are low-skilled, denoted by l, and are endowed with $\bar{l}$ manual labour.

Young workers supply labour to the firm and earn an income of $y_{i,t} = \{q_t\bar{h}, w_t\bar{l}\}$, where q_t (w_t) denotes the high-skilled (low-skilled) wage per unit of labour.

[11] While I focus on owner-occupied housing, the model implicitly embeds a rental market. When the rental market is perfectly competitive, households are indifferent between renting and buying housing. I explore this feature in Section V.D.3.

[12] I do not model bequest. This allows me to remove the persistence in ownership and rather study households' changing incentives in response to climate change.

2.3.2 Climate Risk and Housing Capital

The economy is exposed to physical climate risks and floods occur in each period from extreme weather events (e.g., pluvial floods, hurricanes and torrential rains) and gradual changes like sea-level rise. Let $\gamma_{t+1} \in [0,1]$ denote the probability that a given household experiences damages from a flood in period, $t+1$. This probability is common among households and increases deterministically over time. By the law of large numbers, γ_{t+1} corresponds to the fraction of households experiencing climate-related damages in any period $t+1$. Following Fried (2022), I model idiosyncratic climate damages. Let $\xi_{i,t+1} \in [0,1]$ denote the idiosyncratic losses of a given household, i, in period, $t+1$, which follows some distribution, $F(\xi_{i,t+1})$ that is i.i.d. across households. This reflects that flooding events may hit certain households harder than others. However, since idiosyncratic risk can be diversified, only the expectation of losses matters for pricing. Denote by $\mu_L \in [0,1]$ the expected loss, as a fraction of housing capital, conditional on being hit by a flood. This represents the common, non-diversifiable component of losses. Then, the expected idiosyncratic losses are given by:

$$\begin{aligned}\mathbb{E}(\xi_{i,t+1}) &= \mathbb{E}\left(\xi_{i,t+1}\middle|\text{Hit by the flood}\right)\cdot\mathbb{P}(\text{Hit by the flood})\\ &= \mu_L\gamma_{t+1}\end{aligned}$$

Climate-related damages reduce the amount of housing that can be resold. For a given household i, the housing capital remaining in period $t+1$ is given by:

$$L_{i,t+1} = (1-\xi_{i,t+1})\,L_{i,t}$$

Physical climate events not only destroy part of the housing stock, but also degrade land. Land degradation occurs over a quarter of the Earth's ice-free land area and climate change accelerates the rate and scale of ongoing land degradation processes and generates new degradation patterns. Climate change will further exacerbate land

degradation processes through increasing floods, erosion, soil salinity, landslides, and sea level rise IPCC (2019). These degradation processes can render previously habitable land unsuitable for development, thereby adversely affecting its long-term usability.[13]

Denote the supply of livable land (cf. Burzyński, Deuster, Docquier, and De Melo (2019)) in a given period by $\bar{L}_t$. Consistent with the macroeconomic literature analyzing land and long-run economic - and house price growth, I assume that the supply of livable is fixed in the long run.[14] As a result of land degradation, the supply of houses evolves dynamically over time and follows the law of motion:

$$\begin{aligned}\bar{L}_{t+1} &= \int_0^1 (1 - \xi_{i,t+1})\, di \cdot \bar{L}_t \\ &\overset{\text{LLN}}{=} (1 - \mu_L \gamma_{t+1}) \cdot \bar{L}_t\end{aligned}$$

Hence, by the law of large numbers, the supply of habitable land falls in each period $t+1$ by a fraction $\mu_L \gamma_{t+1}$. As land degrades, rebuilding housing in the affected part of the region becomes impossible. While new homes could be constructed in unaffected parts of the regions, this would still mean that the same number of households must share a smaller amount of land. An alternative way to interpret this supply reduction is as an increase in housing costs, which arise from increased construction expenses in safer areas or potential regulatory restrictions on development in flood-prone zones.

[13] In Section V, I allow households to prevent such degradation through climate change adaptation.

[14] See for example Ricardo (1817), who shows that economic growth benefits landlords disproportionatly due to the fixed nature of land. Nichols (1970) includes land as fixed production factor in a Solow model to show that house prices grow at the same rate as output in the steady state. Also Hansen and Prescott (2002) build a one-good, two-sector overlapping generations (OLG) model land is in fixed supply. More recently, Grossmann, Larin, and Steger (2025) consider a two-good, two-sector infinitely-lived agent model in which the land development sector becomes inactive in the long run. Combined with differences in the intensity by which land is used in different sectors, the fixed nature of land explains the rise in real house prices in the long run as observed in the data. Finally, Saiz (2010) shows empirically that the fraction of undevelopable land is higher in areas where there are regulatory or geographical constraints. This is particularly true for coastal cities, such as Miami, San Francisco, and New Orleans.

2.3.3 Housing Market Dynamics and Financial Markets

There is one housing market on which all home purchases and sales take place. The market opens after the flood, which occurs at the start of the period. Define $S_{i,t}$ as the net savings of a young household, i in period t, after the purchase of housing capital:

$$S_{i,t} = y_{i,t} - p_t L_{i,t}$$

This can be positive or negative, depending on whether a given household i is a net lender or borrower:

$$S_{i,t} \begin{cases} \geq 0 & \text{net lender} \\ < 0 & \text{net borrower} \end{cases}$$

Households earn the risk-free rate of return, r, on their savings. Households may lend to others who have insufficient resources to finance the purchase of their housing capital. Lending takes place against collateral, and the housing capital purchased backs the mortgage contract. However, destroyed housing capital has zero liquidation value, indicating that borrowers risk default. Therefore, borrowers hence pay the risky rate of return, $\hat{r}_{t+1} \geq r$.[15] Default occurs when that mortgage is "under water". That is, when the revenue from selling the undamaged housing capital is smaller than the value of the amount borrowed (including interest):

$$p_{t+1} L_{i,t+1} \leq (1 + \hat{r}_{t+1})(-S_{i,t})$$

Define the loan-to-value ratio as

$$LTV_{i,t+1} = \frac{(1 + \hat{r}_{t+1})(-S_{i,t})}{p_{t+1} L_{i,t}}$$

The condition implicitly defines a threshold on the climate damages above which a

[15] Note that there is no risk-premium, as households are financially risk-neutral due to the quasi-linearity of the utility function.

homeowner defaults:

$$\hat{\xi}_{i,t+1} = 1 - LTV_{i,t+1}$$

Accordingly, the probability of default is given by

$$\chi_{i,t} = \mathbb{P}\left(\xi_{i,t+1} \geq \hat{\xi}_{i,t+1}\right) = \left(1 - F\left(\hat{\xi}_{i,t+1}\right)\right)$$

2.4 Equilibrium

2.4.1 Household Optimization Problem

Households maximize utility subject to the budget constraint and a limited liability constraint:

$$\begin{aligned} \max_{c_{i,t+1}, L_{i,t}, S_{i,t}} \mathbb{E}\left(U(c_{i,t+1}, L_{i,t})\right) &= \mathbb{E}_t\left(c_{i,t+1}\right) + v\left(L_{i,t}\right) \\ s.t. \quad y_i &\leq p_t L_{i,t} + S_{i,t} \\ c_{i,t+1} &\leq \max\{p_{t+1}(1 - \xi_{i,t+1})L_{i,t} + (1 + \hat{r}_{t+1})S_{i,t}, 0\} \\ c_{i,t+1}, L_{i,t} &\geq 0. \end{aligned}$$

where $\mathbb{E}_t$ denotes expectations formed at date t.[16]

Optimal Demand for Housing Capital

The optimal demand for housing capital in a given period t determines its price:

[16] Note that there is no no-bubble constraint in the framework. In overlapping generation models, bubbles arise when agents purchase an asset purely for resale value, rather than for the real return it provides. However, in this model, house prices remain tied to their fundamental value due to several elements. First, perfect foresight ensures that households correctly anticipate the evolution of climate risk, land degradation, and future house prices, preventing speculative expectations that could fuel a bubble. Moreover, housing provides direct utility to households rather than being solely a speculative asset. As a result, house prices in the long term reflect the expected future benefit of homeownership, which is constrained by the marginal utility of housing consumption rather than speculative resale value. This ensure that the transversality condition remains satisfied.

Lemma 1. *The demand for housing capital of each household i in period t is given by*

$$L_t^* = v'^{-1}\left((1+r)p_t - (1-\mu_L\gamma_{t+1})\,p_{t+1}\right)$$

Accordingly, the price of housing capital in a given period, t, becomes

$$p_t = \frac{(1-\mu_L\gamma_{t+1})p_{t+1} + v'\left(L_t^*\right)}{(1+r)}$$

This is a standard asset pricing equation, indicating that the price of housing capital today is equal to the discounted value of the benefits from owning housing. The benefits of owning housing consist of two parts. First, there are marginal benefit to owning housing capital, which is captured by $v'\left(L_t^*\right)$ (the 'dividend'). Second, the owner reaps the revenue from selling the undamaged housing capital at the start of the next period (the 'resale value'). The revenue per unit of housing capital owned is given by the future house price, p_{t+1}, which is discounted for the fraction of expected damages. As a result, demand for housing weakens and current house prices are thus discounted for the exposure to future climate risk (e.g., Bernstein et al., 2019; Baldauf et al., 2020; Bosker et al., 2019). Hence, house prices decline in *future* climate risk, γ_{t+1}.

Demand for Household Debt

Household debt follows residually. Households with net savings lend to others households while households with negative savings take out a mortgage.

2.4.2 Equilibrium and Market Clearing

A competitive equilibrium is an allocation $\{c_{t+1}, L_t, S_t\}_{t=0}^T$ and prices $\{p_t\}_{t=0}^T$, such that in each period, t, given prices, households maximize lifetime utility and all markets clear.

Housing market

Total housing demand equals total housing supply, so that $\int_0^1 L_{i,t}^* di = \bar{L}_t$. Therefore, housing market equilibrium requires

$$\bar{L}_{t+1} = (1 - \mu\gamma_{t+1})\, \bar{L}_t.$$

The housing market clearing condition pins down the equilibrium price of housing capital:

$$p_t^* = \frac{(1 - \mu_L\gamma_{t+1})\, p_{t+1} + v'\left(\bar{L}_t\right)}{1 + r}$$

Forward substitution gives

$$p_t^* = \sum_{j=t}^{\infty} \left(\frac{1}{1+r}\right)^{j-t+1} \left[v'\left(\bar{L}_j\right)\right] \prod_{\iota=t}^{j-1} (1 - \mu_L\gamma_{\iota+1})$$

Hence, as the housing stock is traded across generations, and households have perfect foresight, house prices are forward-looking. The expression reveals that climate change influences house prices through an additional channel, which is the rising scarcity of housing. Households are risk averse with respect to housing consumption - which can be considered a relatively more essential good than their non-durable consumption. This risk aversion is reflected by the concavity of $v(L)$ in housing, L. When the supply of housing decreases due to climate-related damages, the remaining housing supply becomes scarcer. This increases the value households place on owning an additional unit of housing, as reflected by a rise in the marginal utility of owning housing. A higher marginal utility of owning housing raises the willingness to pay, thus driving up house prices. Hence, while houses exposed to climate *risk* face a price discount in the market, climate-related *damages* (i.e., the materialization of climate risk) drive up contemporaneous house prices.

Proposition 1. Let climate risk increase in all future periods by a factor $\sigma > 1$ (i.e.,

future climate risk is given by $\{\sigma\gamma_{t+1}, ..., \sigma\gamma_\infty\}$). The price of housing capital rises in σ if

$$\underbrace{-\frac{v''(\bar{L}_j) \cdot \bar{L}_j}{v'(\bar{L}_j)}}_{RRA} \geq 1 \tag{2.1}$$

Proof: See Appendix A.1

If households are sufficiently risk-averse with respect to their consumption of housing - that is, households are more risk-averse with respect to their housing consumption than their consumption of the non-durable consumption good -, the scarcity effect dominates in the general equilibrium.[17]This leads to a rise in house prices in the long run. While the initial loss of habitable land has a negligible effect on the utility households derive from owning housing, the continued reduction in the housing supply raises the marginal utility of owning housing, producing an increasingly strong upward pressure on house prices over time.

The two opposing effects on house prices can be intuitively understood through geographical variation in climate risk exposure. Consider a region with two distinct types of housing stocks. That is, a fraction $f(\gamma_t)$ of all houses are located on high elevation (e.g., on a hill) and the expected loss conditional on being hit for these houses is given by $\underline{\mu_L}$. The remaining houses are located on low elevation (e.g., at the waterfront) and the expected loss conditional on being hit for these houses is given by $\bar{\mu_L}$, with $1 > \bar{\mu_L} > \underline{\mu_L} > 0$.

If the risk exposure is common across houses in the region and housing markets are unsegmented, house prices adjust in equilibrium to ensure that households are indifferent between purchasing housing in the region with a high or low risk exposure. Then, house prices in each respective region are given by

[17] This result is analogous to the asset pricing result that the substitution effect dominates the income effect when the RRA is greater than one. In this context, it is also the stronger sensitivity to changes in marginal utility which cause the scarcity effect to outweigh the discount effect.

$$p_t^{low} = \frac{\left(1 - \underline{\mu}_L \gamma_{t+1}\right) p_{t+1} + v'(\bar{L}_t)}{(1+r)}$$
$$p_t^{high} = \frac{\left(1 - \bar{\mu}_L \gamma_{t+1}\right) p_{t+1} + v'(\bar{L}_t)}{(1+r)}$$

The differences in risk exposure results in implicit price segmentation, since houses with a higher risk exposure trade at lower prices than houses with a lower risk exposure. Intuitively, this implies that houses on higher elevation are a hedge against houses on lower elevation. In aggregate, house prices are given by

$$p_t = f(\gamma_t) \cdot p_t^{low} + (1 - f(\gamma_t)) \cdot p_t^{high}$$

The supply of housing with a high climate risk exposure decreases faster. Over time, this changes the composition of the housing stock in the region, as houses with a lower risk exposure have a higher likelihood to remain. As houses with high risk becomes increasingly scarce, this shifts housing demand to low-risk housing, pushing up its price.

Corollary 1. *Within a region, houses on higher elevation trade at higher prices than those on lower elevation. Over time, aggregate house prices rise.*

In the remainder of this analysis, I focus on one type of housing stock within the given region.

Financial market

Aggregate income of young households must in equilibrium equal the aggregate investment in housing. Hence,

$$\int_0^1 y_i di = p_t \bar{L}_t,$$

where the aggregate labour income of the young is:

$$\int_0^1 y_i di = \phi q + (1-\phi)\, w.$$

In equilibrium, the total savings of labour income must be large enough to cover the purchase of the stock of houses. This indicates that at least one type of households must have positive savings. Since high-skilled households earn higher wages, these households are net lenders. Low-skilled are either net lenders or net borrowers and the volume of mortgage credit in the economy, m, is given by

$$m_t = \max\left\{0, (1-\phi)\left(p_t \bar{L}_t - w\right)\right\}$$

i.e., the size of mortgage credit in the economy is equal to the value of the housing stock owned by low-skilled households, net of their income.

Corollary 2. *The volume of credit rises in climate risk.*

2.5 Adapting to Climate Change

I introduce private adaptation to climate change, allowing households to invest in self-protective measures that increase their resilience and reduce vulnerability to flooding. Private adaptation measures, such as storm-proof windows, flood-proof floors, or the fortification of one's home do not alter the probability of climate-related damages in a given period (γ_t) or the progression of climate risk ($\gamma_{t+1}, ..., \gamma_\infty$). Rather, by investing in adaptation, households reduce the idiosyncratic losses they experience due to flooding. As a result, household's private adaptation measures directly influence the rate at which inhabitable land degrades, and thus the speed at which the housing supply shrinks.[18]

[18] Even when measures are implemented to avoid or reverse land degradation, there will be some residual degradation with high likelihood (IPCC, 2019).

2.5.1 Climate Change Adaptation

Households invest in climate change adaptation at the time they purchase housing capital. Denote by $x_{i,t} \in [0, 1)$ the choice of adaptation of household i in period t. This investment comes at a cost. Specifically, the investment costs are given by $\psi(x_{i,t}, L_{i,t}) = \frac{1}{2} L_{i,t}(x_{i,t})^2$. The costs increase with the amount of housing capital, as larger houses require more significant investments, such as a greater number of storm-proof windows, to achieve the same level of protection (Fried, 2022). Moreover, the investment rise at an accelerating rate in the choice of adaptation, indicating that even the most ambitious investments cannot entirely prevent climate-related losses and damages (UNEP, 2022). For simplicity, I assume that the adaptation infrastructure fully depreciates at the end of each period. That is, households must reinvest in adaptation in every period.[19]

By adapting to climate change, households protect themselves against climate-related damages in the next period. Let the choice of adaptation, $x_{i,t}$, represent the fraction of idiosyncratic losses which are prevented due to the investment in resilience. Adaptation thus leads to a leftward shift in the distribution of losses by $x_{i,t} \cdot \mu_L \gamma_{t+1}$. In expectation, the losses experienced by a given household, $\xi_{i,t+1}$, are given by:

$$\mathbb{E}\left(\xi_{i,t+1}\right) = \left(1 - x_{i,t}\right) \mu_L \gamma_{t+1}$$

A household with $x_{i,t} = 0$ does not undertake any measures to reduce idiosyncratic losses, while $x_{i,t} \to 1$ indicates that the household has perfectly adapted to climate change and has nearly eliminated all expected losses. Define x_t as the aggregate private

[19] The main insights are not sensitive to this assumption. Suppose, for example, that adaptation infrastructure only depreciates when the household experiences damages due to flooding (with probability γ, but remains intact if the household is not hit (with probability $(1 - \gamma)$. In this case, households who are not affected by the flood sell both the house and the adaptation infrastructure. Assuming that the adaptation infrastructure is marketable, yet inseparable from the house, and trades at its fair value, households still invest optimally in adaptation. This is because the house price reflects the expected value of selling the adaptation infrastructure along with it. Due to the forward-looking nature of house prices, households implicitly account for the expected value of their adaptation investment for all future generations. Note that, as the marginal benefits of adaptation investment increase when it can be resold, households optimally invest more in adaptation than in the full-depreciation benchmark.

investment in adaptation, i.e.

$$x_t = \int_0^1 x_{i,t} di$$

By its virtue of preserving housing capital, climate change adaptation reduces the rate at which the supply of inhabitable houses declines. More specifically, when households adapt to climate change, the supply of inhabitable houses evolves according to the following law of motion:

$$\begin{aligned} \bar{L}_{t+1} &= \int_0^1 (1 - \xi_{i,t})\, di \cdot L_t \\ &\overset{\text{LLN}}{=} (1 - (1 - x_t)\mu_L \gamma_{t+1})\, \bar{L}_t \end{aligned}$$

The investment in adaptation in period t prevents some of the reduction in the housing supply in the subsequent period, $t + 1$. Therefore, adaptation constitutes an intertemporal investment, leaving the current housing supply, $\bar{L}_t$, unaffected. Consequently, adaptation does not increase the utility of owning housing capital, $v(L)$. Instead, by reducing the damage to housing, adaptation ensures that more of the housing stock stays intact and can be resold in the next period. This gives older households more resources to spend on non-durable goods. Adaptation also benefits future generations. By protecting the housing stock, it ensures that more houses remain available for them to live in and derive utility from. In this way, adaptation investments also benefit future households by preserving housing availability.

Note on Insurance Markets Investing in adaptation fundamentally differs from purchasing insurance, since adaptation aims at prevention, whereas insurance offers monetary compensation after losses occur. While purchasing insurance is an effective measure to reduces the impact of climate risk on household wealth, the ex-post compensation provided cannot alleviate the reduction in the supply of inhabitable houses. Demand for insurance is not separable from households' adaptation choice, however, as climate-related damages directly affect the value of the insured good (Mayers and Smith Jr, 1983). Hence, climate risk insurance affects the private choice of adaptation in

the general equilibrium. I explore this in more detail in a model extension, in Section VIII.A.

2.5.2 Unconstrained Private Choice of Adaptation

Household Optimization Problem

When households adapt to climate change, the household maximization problem is given by

$$\begin{aligned}\max_{c_{i,t+1},L_{i,t},S_{i,t},x_{i,t}} \mathbb{E}\left(U(c_{i,t+1},L_{i,t})\right) &= \mathbb{E}_t\left(c_{i,t+1}\right)+v\left(L_{i,t}\right)\\ s.t. \quad y_i &\leq \left(p_t+\frac{1}{2}x_{i,t}^2\right)L_{i,t}+S_{i,t}\\ c_{i,t+1} &\leq \max\left\{p_{t+1}\left(1-\xi_{i,t+1}\right)L_{i,t}+\left(1+\hat{r}_{t+1}\right)S_{i,t},0\right\}\\ c_{i,t+1},x_{i,t},L_{i,t} &\geq 0\end{aligned}$$

where $\mathbb{E}_t$ denotes expectations formed at date t.

Optimal Demand for Housing and Adaptation

When households adaptation to climate change, this affects their demand for housing capital. First, by reducing vulnerability to climate risk, investments in adaptation ensure that a larger fraction of housing capital remains undamaged. This increases the per unit revenue of selling housing once households turns old, thus raising housing demand. However, the investment in adaptation absorbs part of households' savings, leaving less resources to be allocated to housing consumption.

Lemma 2. *When households adapt to climate change, the demand for housing capital of a given household, i, in a given period, t, is given by*

$$L_t^* = v'^{-1}\left(\left(1+r\right)\left(p_t+\frac{\theta}{2}x_{i,t}^{*2}\right)-\left(1-(1-x_{i,t}^*)\mu_L\gamma_{t+1}\right)p_{t+1}\right)$$

and the price of housing capital in a given period, t, is given by

$$p_t = \frac{\left(1 - (1 - x^*_{i,t})\mu_L \gamma_{t+1}\right) p_{t+1} + v'(L^*_t)}{(1+r)} - \frac{1}{2} x^{*2}_{i,t}$$

The above expression indicates that the total amount spent per unit of housing capital, i.e., $p_t + \frac{1}{2}x^{*2}_{i,t}$, must equal the discounted value of the benefits from owning housing capital. This expression reveals the trade-off between the present costs and future benefits of adaptation, as adaptation requires an upfront investment cost while it only generates benefits to households once they sell their housing. This trade-off determines the private choice of adaptation in equilibrium, with households investing in adaptation as long as its marginal benefits outweigh its marginal cost.

Lemma 3. *The optimal private choice of adaptation of a given household i is given by*

$$x^*_{i,t} = \frac{\mu_L \gamma_{t+1} \cdot p_{t+1}}{(1+r)}$$

The optimal private choice of adaptation increases in climate risk exposure (γ_{t+1}), as well as in the expected losses when hit by the flooding event, μ_L, since both parameters increase the expected damages to the housing capital owned. Therefore, a rise in households' climate risk exposure strengthens their incentives to invest in adaptation over time.

The optimal private choice of adaptation is crucially influenced by house prices, as the house price reflects the value at risk from flooding to households. Price signals, therefore, play a crucial role in determining private adaptation decisions. As discussed in Section IV.B., house prices are forward-looking. They not only reflect the reduction in households' climate risk exposure due to adaptation efforts but also incorporate the benefits adaptation provides for future generations. By investing in adaptation, households preserve more of the housing stock for the future, making housing less scarce over time. This reduced scarcity weakens the rise in the marginal utility of owning housing. Since this intergenerational benefits is capitalized into house prices, house-

holds—guided by price signals—effectively internalize the long-term benefits of their adaptation investments.[20] Hence, price signals prevent the "tragedy of the horizon" effect, i.e., where a short-term focus of economic agents overlooks long-term climate risks and their impacts on future generations (Carney, 2015).

To illustrate this point, suppose that an unconstrained social planner maximizes utilitarian welfare , i.e.

$$\max_{x_{S,t}} \sum_{t=0}^{\infty} \left(\frac{1}{1+r}\right)^t \left[-(1+r)\frac{1}{2}\bar{L}_t \cdot x_{S,t}^2 + v(\bar{L}_t)\right]$$

subject to

$$\bar{L}_j = \bar{L}_t \prod_{\iota=t}^{j-1} (1-(1-x_{S,\iota})\mu_L \gamma_{\iota+1})$$

This gives:

$$x_{S,t}^* = x_{i,t}^*$$

Proposition 2. The optimal private choice of adaptation is efficient.

Proof: See Appendix A.2

Households determine their private choice of adaptation based on market signals. Consequently, Proposition 2 is sensitive to two underlying assumptions. First, within this framework, climate risk is accurately capitalized into house prices. Although empirical studies show that climate risk is gradually being incorporated into house prices (see e.g., Baldauf et al., 2020; Bernstein et al., 2019; Bosker et al., 2019), it is crucial to assess whether prices in the housing market sufficiently reflect the actual climate risk exposure of a given region. If climate risk is not properly accounted for in market pricing — due to factors such as heterogeneity in beliefs about climate change (see e.g., Bakkensen

[20] Note that there is no moral hazard in adaptation by borrowers. This is because borrowers bear the full consequences of their adaptation decisions - as a higher adaptation investment increase the revenue when selling the house. Moreover, there is no information asymmetry on the size of the damages between borrowers and lenders, and borrowers repay the mortgage (or default) right after the flood occurs and housing markets open. Hence, there is no agency problem when households borrow.

and Barrage, 2021; Baldauf et al., 2020) or buyers' limited sophistication (see e.g., Bernstein et al., 2019) prices may fail to signal the risks faced by households. As a result, households would underinvest in adaptation, leaving them vulnerable to the impacts of climate change. The accurate pricing of climate risk in housing markets is therefore crucial to incentivize households to adapt optimally.

Second, for Proposition 2 to hold, market signals must accurately reflect the social benefits of a having an additional unit of housing available for the next generation. If a social planner maximizes utilitarian welfare and weights the utility of different generations using market discount rates, the private optimum and social optimum coincide. However, if the social planner assigns a larger weight to the welfare of future generations (i.e., a discount rate lower than the market discount rate), the value of preserving an additional unit of housing would have a higher social value than market prices reflect. In this case, households would underinvest in adaptation from a social perspective.

Corollary 3. *If the social planner evaluates the welfare of future generations using a discount rate of $r^{SP} \in [0,1]$ with $r^{SP} < r$, unconstrained households **underinvest** in adaptation. Denote by Ω the social adaptation gap, which is defined as the difference between the private choice of adaptation and the social optimum. In a given period, t, the size of the social adaptation gap is given by*

$$\Omega_t = \frac{\mu\gamma_{t+1}}{(1+r)} \cdot \sum_{j=t+1}^{\infty} \left(\left(\frac{1}{1+r^{SP}} \right)^t - \left(\frac{1}{1+r} \right)^t \right) \left[-(1+r)\frac{1}{2}x_j^2 + v'(L_j) \right] \prod_{i=t+1}^{j-1} \left(1 - (1-x_i)\,\mu\gamma_{i+1}\right)$$

The choice of the appropriate social discount rate has received large attention in the climate change economics literature (see e.g., Stern, 2007; Nordhaus, 2007; Weitzman, 2007), yet disagreements remain at the heart of the climate policy debate (Nordhaus,

2013).[21] While determining the appropriate discount rate for mitigation efforts – which aim to protect the global climate – can be complex (Heal and Millner, 2014), adaptation is fundamentally different. Unlike the global climate, which is a public good that is not traded in the market, housing, a private and tradable asset. Since private adaptation directly protects these market-valued assets, market signals can provide guidance for adaptation investments, even if they do not fully account for broader social welfare considerations.

2.5.3 Equilibrium and Market Clearing

When households adapt to climate change, this changes the housing - and financial market clearing conditions.

Housing market

Total housing demand equals total housing supply, so that $\int_0^1 L_{i,t}^* di = \bar{L}_t$. Therefore, housing market equilibrium requires

$$\bar{L}_{t+1} = \left(1 - (1 - \int_0^1 x_{i,t}^* di)\mu\gamma_{t+1}\right) \bar{L}_t.$$

The housing market clearing condition pins down the equilibrium price of housing

[21] Following the Ramsey rule, the relationship between the equilibrium real return on capital, r^*, and the growth rate of the economy, g^* is given by $r^* = \varrho + \zeta \cdot g^*$, where ϱ denotes the pure rate of time preference, g denotes the growth rate of per capita consumption and ζ denotes the elasticity of consumption (Nordhaus, 2007). Stern (2007) argues that it is immoral to evaluate the welfare of future generations using a social discount rate based on market discount rates. Rather, the author favours an a priori approach, with $\varrho = 0.1\%$, $\zeta = 1$ and $g^* = 1.3\%$. This gives a real return of capital equal to $r^* = 1.4\%$.. Nordhaus (2008) argues that economists have no particular expertise in what is morally right, but must ensure that models replicate reality. Therefore, Nordhaus (2007) advocates a market based approach with $\varrho = 1.5\%$, $\zeta = 2$, and $g^* = 2\%$. This gives a real return on capital equal to $r^* = 5.5\%$. Weitzman (2007) proposed his guess of consensus estimates among economists studying climate change. This gives $\varrho = 2\%$, $\zeta = 2$ and $g^* = 2\%$, translating into a real return on capital equal to $r^* = 6\%$. However, arguing that uncertainty is key to the climate problem, Weitzman (2007) favors a discount rate that declines sharply over time. While the difference in the proposed social discount rates may appear small, small differences lead to large differences in the recommended intensity of climate change mitigation policies (Heal and Millner, 2014).

capital:

$$p_t^* = \frac{\left(1 - (1 - \int_0^1 x_{i,t}^* di)\mu_L \gamma_{t+1}\right) p_{t+1} + v'\left(\bar{L}_t\right)}{1+r} - \frac{1}{2}\int_0^1 x_{i,t}^{2*} di$$

Forward substitution gives

$$p_t^* = \sum_{j=t}^{\infty} \left(\frac{1}{1+r}\right)^{j-t+1} \left[-(1+r)\int_0^1 x_{i,j}^{2*} di + v'\left(\bar{L}_j\right)\right] \prod_{\iota=t}^{j-1} \left(1 - \left(1 - \int_0^1 x_{i,\iota}^* di\right)\mu_L \gamma_{\iota+1}\right)$$

Due to the forward-looking nature of house prices, adaptation efforts reduce the speed at which the housing supply declines. This reduced scarcity dampens the rise in the value households place on owning housing. If Condition (1) holds (see Proposition 1), this scarcity effect dominates in equilibrium. Then, adaptation helps mitigating the effect of climate risk on house prices.

Corollary 4. *Investments in adaptation reduces the rate at which house prices rise.*

Financial market

Aggregate income of young households must in equilibrium equal the aggregate investment in housing and adaptation. Hence,

$$\int_0^1 y_i di = \left(p_t + \frac{1}{2}\int_0^1 x_{i,t}^{2*} di\right) \bar{L}_t,$$

In this case, the volume of mortgage credit in the economy, m, is given by

$$m_t = \max\left\{0, (1-\phi)\left(\left(p_t + \frac{1}{2}\int_0^1 x_{i,t}^{2*} di\right) L_t - w\right)\right\}$$

Corollary 5. *Investments in adaptation reduces the rate at which the volume of mortgage credit rises.*

2.5.4 Endogenous Credit Constraints

Borrowers are protected by limited liability, which can create incentives for highly indebted households to strategically default. In the baseline model, housing capital is collateralized in order to prevent this. However, the collateral itself is exposed to climate risk, as floods directly reduce both the quantity and value of housing that can be pledged. Because of the deterministic nature of climate risk, mortgage creditors anticipate these potential losses and adjust their lending accordingly. Rational lenders therefore ensure that household debt (including interest) does not exceed the expected liquidation value of undamaged housing capital in the next period (Kiyotaki and Moore, 1997; Sastry, Forthcoming).

The expected liquidation value of the collateral depends on the economy's climate risk exposure and the adaptation efforts undertaken by borrowers. By investing in adaptation, borrowers can mitigate potential losses, thereby directly influencing the liquidation value of the collateral. Adaptation investments are made privately, however and mortgage creditors are unable to individually verify the investment households have made in adaptation after credit has been extended.[22] Mortgage creditors thus form expectations on the choice of adaptation of borrowers, denoted by $\mathbb{E}\left(\bar{x}_{l,t}\right)$.[23] The credit constraint then becomes:

$$(1+\hat{r}_{t+1})(-S_{l,t}) \leq \left(1-\left(1-\mathbb{E}\left(\bar{x}_{l,t}\right)\right)\mu_L\gamma_{t+1}\right)p_{t+1}\cdot L_{l,t}$$

where

$$S_{l,t} = w - \left(p_t + \frac{1}{2}x_{l,t}^2\right)L_{l,t} < 0$$

The left-hand side of the equation represents mortgage credit demanded by borrowers, which depends on current house prices, p_t, borrowers' choice of adaptation, $x_{l,t}$,

[22] Even if creditors could, it is nearly impossible to verify that adaptation measures are maintained and remain functional at the time of the flood.

[23] In a symmetric equilibrium, creditors' expectations are correct.

and their demand for housing, $L_{l,t}$. The right-hand side reflects the expected liquidation value of the undamaged collateral. This liquidation value is influenced by the economy's climate risk exposure, γ_{t+1}, the expected choice of adaptation of borrowers, $\mathbb{E}\left(\bar{x}_{l,t}\right)$, and future house prices, p_{t+1}. Since there is no aggregate uncertainty, mortgage creditors have perfect foresight on future house prices.

Climate change impacts the credit constraint through multiple channels. Consider first the expected liquidation value of the collateral. While future house prices rise due to the reduced housing supply, house prices are fully recursive and, therefore, this is entirely reflected in the current house price. In other words, as the price at which a given unit of housing capital can be resold rises, this also increases the costs of buying that unit of housing in the first place (see Proposition 1).[24] Additionally, higher climate risk exposure increases the need for adaptation measures, driving up investment costs. Hence, a rise in climate risk increases in the down payment required from borrowers, tightening the credit constraint over time.[25]

Equilibrium with Credit Constraints

As indicated in Section IV.B., high-skilled households are net lenders in equilibrium. Low-skilled households are either net lenders or net borrowers. When these households borrowers, they maximize expected utility subject to the budget constraint, lim-

[24] Unlike in Kiyotaki and Moore (1997), where asset prices are forward-looking but subject to shocks that generate endogenous amplification through collateral constraints, house prices in this model are fully recursive and determined in closed form. Since future prices are pinned down by the scarcity of housing and households' adaptation choices, credit constraints tighten not through asset price declines, but through rising housing values driven by the increasing scarcity of housing.

[25] Sastry (Forthcoming) documents empirically that lenders screen for flood risk and, when they retain residual exposures to it, require higher down payments.

ited liability constraint, and the credit constraint:

$$\begin{aligned}
\max_{c_{l,t+1},L_{l,t},S_{l,t},x_{l,t}} \mathbb{E}\left(U(c_{l,t+1},L_{l,t})\right) &= \mathbb{E}_t\left(c_{l,t+1}\right) + v\left(L_{l,t}\right) \\
s.t. \quad w &\leq \left(p_t + \frac{1}{2}x_{l,t}^2\right) L_{l,t} + S_{l,t} \\
c_{l,t+1} &\leq \max\left\{p_{t+1}\left(1-\xi_{l,t+1}\right) L_{l,t} + \left(1+\hat{r}_{t+1}\right) S_{l,t}, 0\right\} \\
-(1+\hat{r}_{t+1})S_{l,t} &\leq \left(1-\left(1-\mathbb{E}\left(\bar{x}_{l,t}\right)\right)\mu_L\gamma_{t+1}\right) p_{t+1}L_{l,t} \\
c_{l,t+1}, L_{l,t}, x_{l,t} &\geq 0
\end{aligned}$$

Optimal Demand for Housing and Adaptation

Due to credit constraints, low-income households have limited financial resources to finance the purchase housing capital and their investment in adaptation. In equilibrium, low-income households borrow up to the point where the constraint binds:

Lemma 4. *The demand for housing capital of credit constrained, low-income households is given by:*

$$L_{l,t}^* = \frac{(1+r_{t+1})w_t}{(1+r_{t+1})\left(p_t + \frac{1}{2}x_{l,t}^2\right) - \left(1-\left(1-\mathbb{E}(\bar{x}_{l,t})\right)\mu_L\gamma_{t+1}\right)p_{t+1}}$$

where $\mathbb{E}(\bar{x}_{l,t}) = x_{l,t}^*$ *in a symmetric equilibrium. The choice of adaptation of credit constrained, low-skilled households,* $x_{l,t}^*$*, is given by*

$$x_{l,t}^* = \frac{\mu_L\gamma_{t+1}\cdot p_{t+1}}{(1+r_{t+1})(1+\lambda_t)}$$

with $\lambda_t \geq 0$ *the shadow price of the credit constraint.*

When credit constraints bind, households cannot afford the optimal amount of housing capital and therefore consume less housing. Due to the quasi-linearity of preferences and diminishing marginal utility of housing, the marginal utility of housing becomes higher for constrained households than for the unconstrained ones. This is captured by

a strictly positive shadow price of the constraint, λ_t, which reflects the utility gain of relaxing the constraint by one unit.

The binding constraint distorts the intertemporal allocation decision, which has important implications for adaptation. Adaptation is a forward-looking investment: it increases the resale value of housing by mitigating future climate-related damages. Because credit households must finance adaptation jointly with housing capital, but are liquidity constrained, their effective marginal cost of adaptation is higher. As these households are limited in the extent to which they can borrow against the future, they discount the benefits of adaptation more heavily, essentially behaving as if they are more impatient.[26] As a result, constrained households optimally allocate a larger share of their limited budget to housing capital, which provides utility in the present, and invest less in adaptation, which enhances resilience against future climate risks.

Proposition 3. Credit constrained, low-income households adapt relatively less to climate change:

$$x_l^* < x^*$$

Proof: See Appendix A.3

Proposition 3 has several key implications. Since the adaptation choice, $x_{l,t}$, represents the *fraction* of idiosyncratic losses prevented, the underinvestment in adaptation by credit-constrained households implies that these households protect a smaller share of their housing wealth. Consequently, these households remain more vulnerable to climate risks. When a flooding event occur, credit-constrained households experience a disproportionately larger expected loss in housing wealth, reinforcing existing wealth inequality. In addition, the underinvestment in adaptation by credit-constrained households accelerates the reduction in the supply of habitable houses. This exacerbates scarcity over time and generates intergenerational spillovers: future generations face

[26] The wedge between the marginal utility of housing and the (discounted) returns to adaptation does not reflect a change in preferences, but rather a financing friction. It gives rise to a persistent private adaptation gap, driven by limited access to credit, rather than by differences in climate exposure or willingness to adapt.

scarcer housing supply and their welfare is therefore lower.[27] Denote by Λ_t the private adaptation gap, which is defined as the optimal private choice of adaptation relative to the constrained choice of adaptation:

$$\Lambda_t = \frac{x^*_{h,t}}{x^*_{l,t}} = (1 + \lambda_t)$$

Proposition 4. When the utility function of housing ($v(L)$) is characterized by constant relative risk aversion (CRRA), the private adaptation gap rises in climate risk.

Proof: See Appendix A.4

The private adaptation gap widens over time as habitat becomes increasingly scarce. The mechanism is dynamic: underinvestment by one generation raises housing scarcity and therefore increases the marginal utility of housing for the next generation. This results in a higher shadow price of the credit constraint. In essence, housing becomes increasingly important relative to future consumption, leading credit-constrained households to allocate a growing share of their resources toward housing capital rather than adaptation. This leads to a persistent widening of the private adaptation gap across generations.

Rental Markets and Effective Adaptation

Credit constraints prevent households from effectively reducing their vulnerability to climatic impacts, leading to underinvestment in adaptation. Would the economy as a whole benefit if credit-constrained households relied on households with deeper pockets individuals to mitigate climate impacts? I explore whether it is more efficient for credit-constrained households to rent housing capital, rather than purchasing it. Recall

[27] Due to the rising scarcity of houses, the value at risk increases. Therefore, unconstrained households invest more in adaptation in an economy where a fraction of households is credit constrained, compared to an economy where a fraction of households is credit constrained, compared to an economy without binding credit constraints. However, this does not represent inefficient overinvestment. The adaptation choice of unconstrained households remains first-best, as they simply respond to the rising marginal benefits of housing for future generations as habitable land becomes scarcer.

that the price of housing capital is given by:

$$p_t + \frac{1}{2}{x_t}^2 = \frac{(1-(1-x_t)\mu_L\gamma_{t+1})\,p_{t+1} + v'(\bar{L}_t)}{(1+r_{t+1})}$$

In a perfectly competitive rental market, the rental price (per unit of housing L_t), Y_t, must be such that (unconstrained) households are indifferent between renting or buying housing. Then, the rental price satisfies

$$\mathrm{Y}_t = v'\left(\bar{L}_t\right)$$

The model implicitly incorporates a rental market, where $v'\left(\bar{L}_t\right)$ represents the imputed rent. The rental price rises over time due to the increased scarcity of inhabitable houses. Nevertheless, it is through the reassignment of ownerships that credit-constrained households become better off by renting housing capital rather than purchasing it.

When households rent rather than buy, the ownership of housing capital remains with the landlord. This removes the need for credit-constrained households to take out a mortgage, allowing them to consume the optimal level of housing without facing credit constraints. The responsibility for investing in adaptation then shifts to the landlord. Adaptation increases the resale value of housing in the future. In a perfectly competitive rental market, rents reflect the full value of protected housing, including these benefits of adaptation. This price signal incentivizes landlords to invest efficiently in resilience. The rental model thereby also overcomes the information problem due to non-verifiable adaptation by allowing prices to reflect the underlying value of the adaptation investment.

In this sense, the rental contract functions as an equity-like arrangement, where landlords – as residual claimants, bear the investment cost and capture the returns through higher rental income and preserved resale value. In contrast to mortgage markets, where adaptation investment by credit-constrained households are hindered by collateral limits, rental markets thus enable more efficient adaptation.

Landlords thus effectively shield credit-constrained households from the climatic impacts they would otherwise face. A key implication is that the rental model ensures that optimal adaptation investments are made across the entire housing stock, not just for homes owned by the unconstrained. This preserves a larger supply of habitable housing over time, benefiting future generations. Moreover, since climate shocks are independent and identically distributed across households, unconstrained households are, in expectation, no worse off when acting as landlords rather than homeowners.

Proposition 5. If perfectly competitive, rental markets leads to more effective adaptation.

Proof: See Appendix A.5

2.6 Quantitative Assessment and Counterfactual Analysis

I quantify the welfare effects of the underinvestment in adaptation over time. For this purpose, I focus on the version of the model which incorporates firms (see Appendix C). I provide a parameterization based on the U.S. economy in the year 2010 and I simulate the model up to 2150 for Florida's coastal area.[28] Given the overlapping generation structure of the model, each time period equals 30 years. I conduct counterfactual analysis to demonstrate welfare effects under different climate change scenarios as projected by IPCC (2023).[29] Specifically, I simulate the model under low greenhouse gas emission-scenarios (SSP1-1.9, SSP1-2.6), an intermediate greenhouse gas emission-

[28] The projections of climate change used are relative to a 1995-2014 baseline. Hence, the climate risk parameter has a value of 0 between 2000 and 2010.

[29] Bilal and Känzig (2024); Cruz and Rossi-Hansberg (2024); Bilal and Rossi-Hansberg (2023) also use projections to measure future impacts of climate change. The authors focus on temperature projections, which closely match the projections of the IPCC under a business-as-usual (i.e. the high greenhouse gas emission) scenario.

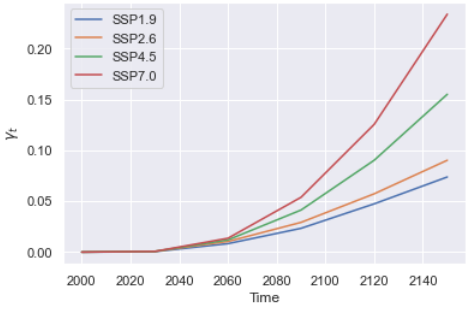

Figure 2.1: The evolution of γ_t under the SSP1-1.9, SSP1-2.6, SSP2-4.5 and SSP3-7.0 scenario.

scenario (SSP2-4.5) and a high greenhouse gas emission-scenario (SSP3-7.0).[30]

2.6.1 The Evolution of Climate Risk

To determine the evolution of climate risk, I assume that γ_t represents the fraction of homes in Florida's coastal area which are at risk of flooding due to future sea level rise.[31] Florida is a low-lying state at the east coast of the United States, and is at high risk of flooding due to sea level rise. Within the next 30 years, approximately 64,000 homes in Florida will be at risk of chronic flooding and 12,000 of those homes are located in the Miami Beach area. This number is expected to grow rapidly, to more than 1 million homes by the end of the century. This implies that Florida alone would account for more than 40 percent of the houses at risk of flooding due to sea level rise in the United States as a whole (Dahl et al., 2018).

To evaluate property-level exposure to sea level rise in Florida's coastal areas, I rely

[30] The SSP$x-y$ scenarios describe different climate futures depending on socio-economic trends underlying the scenario (x) and the approximate level of radiative forcing (in watts per square meter) resulting from the scenario in the year 2100 (y).Under SSP1-1.9 (SSP1-2.6), global warming remains approximately below 1.5 (2.0) degrees Celsius above 1850-1900 in the year 2100, which is the target of the Paris Agreement. This scenario requires net zero CO2 emissions by 2050 (in the second half of the century). SSP2-4.5 is in line with the aggregate Nationally Determined Contribution emission levels by 2030. Under this scenario, global warming reaches approximately 2.7 degrees Celsius above 1850-1900 by the end of the century. SSP3-7.0 is a medium to high climate change scenario. Under this scenario, global warming reaches approximately 3.6 degrees Celsius above 1850-1900 by the end of the century.

[31] Specifically, I focus on properties that would be flooded for 10 feet of sea level rise.

on the estimates provided by Bernstein et al. (2019).[32] I focus on aggregate exposure estimates, measuring the total number of properties at risk of flooding for varying levels of future sea level rise.[33] These estimates provide the number of properties expected to be flooded for different levels of future sea level rise. To approximate the evolution of the fraction of houses at risk of flooding due to future sea level rise (γ_t) under different scenarios of sea level rise, I use the NASA Sea Level Projection Tool (Garner, Hermans, Kopp, Slangen, Edwards, Levermann, Nowicki, Palmer, Smith, Fox-Kemper, Hewitt, Xiao, Aðalgeirsdóttir, Drijfhout, Golledge, Hemer, Krinner, Mix, Notz, Nurhati, Ruiz, Sallée, Yu, Hua, Palmer, and Pearson, 2021; Fox-Kemper, Hewitt, Xiao, Aðalgeirsdóttir, Drijfhout, Edwards, Golledge, Hemer, Kopp, Krinner, Mix, Notz, Nowicki, Nurhati, Ruiz, Sallée, Slangen, and Yu, 2021; Garner, Kopp, Hermans, Slangen, Koubbe, Turilli, Jha, Edwards, Levermann, Nowicki, Palmer, and Smith, in prep.). This tool visualizes the median projections of global and regional sea level rise, relative to a 1995-2014 baseline. These projections are based on IPCC (2023). Projections are provided for various regions and cities in Florida. As there is relatively little variability in their projection, I focus on the projections for the Miami-beach area.[34] By the end of the century, this

[32] Bernstein et al. (2019) use geographic mapping software to assess each property's vulnerability to sea level rise. Specifically,the authors combine geolocation data of individual properties with projections from the National Oceanic and Atmospheric Administration (NOAA) sea level rise calculator, which identifies regions expected to be underwater under different sea level rise scenarios.

[33] The estimates cover scenarios from 1 to 10 feet of sea level rise. For example, Bernstein et al. (2019) find that 7.2 percent of properties in Florida's coastal areas would be flooded under 3 feet (0.914 meters) of sea level rise, while 50.7 percent would be flooded under 6 feet (1.83 meters).

[34] Projections are provided for Virginia Key, Lake Worth Piert, Trident Pier (Port Canaveral), Dayone Beach, Mayport (Bar Pilots Doc), Fernandina Beach, Vace Key, Key West, Naples, Fort Myers, St. Petersburg, Clearwater Beach, Cedar Key, Apalachicola, Panama City, St. Andrews Bay, and Pensacola. By the end of the century, these regions are expected to experience a sea level rise between 0.64 and 0.73 meters by the end of the century under an intermediate greenhouse gas emission scenario (SSP2-4.5).

Parameter	Description	Value	Source/Target
A	TFP in final-good production	1	Normalization
$\tilde{h}$	Inelastic supply of high-skilled labour	35	Credit allocation target
$\tilde{l}$	Inelastic supply of low-skilled labour	20	Credit allocation target
$\bar{L}$	Initial stock of houses	1	Normalization
α	Capital share in final-good production	0.32	BEA (2010)
η	Relative productivity of intangible inputs	0.67	Credit allocation target
μ_L	Fraction of damages to housing capital	1	Complete losses due to SLR
μ_K	Fraction of damages to tangible capital	0.7	$\mu_L/\mu_K = 0.7$ (Fried, 2022)
ρ	Substitution parameter	0	Cobb-Douglas Production
ϕ	Fraction of high skilled labour	0.3	U.S. Census Bureau (2010)
$\tilde{\omega}$	Bargaining power of innovators (scaled)	0.58	Capital structure target

Table 2.1: Parameter Values

Target	Description	Data	Model
Credit allocation target	Household debt/(Household + corporate debt)	0.68	0.65
Capital structure target	Corporate debt/(Corporate debt + equity)	0.26	0.29

Table 2.2: Targeted Moments

region is expected to experience sea level rise of 0.71 meters under an intermediate greenhouse gas emission scenario (SSP2-4.5). The evolution of the fraction of houses at risk of flooding due to future sea level rise, under the different SSP$x-y$ trajectories, is depicted in Figure 2.1. Under the intermediate climate change scenario, approximately 15 percent of homes are at risk of flooding due to sea level rise by the mid of the next century.

2.6.2 Other Parameters and Functional Form Specifications

Other parameter values are specified in Table 2.1.[35] I use a number of internally and externally calibrated parameters. Externally calibrated parameters are reported

[35] I refer to Appendix C for a description of the version of the model which incorporates firms.

as of 2010 for the Unites States.[36] I internally calibrate the supply of labour and the relative productivity of the distinct types of capital. Specifically, I choose the value of these parameters to target the ratio of household to (non-financial) corporate debt in the U.S. economy in 2010 (Federal Reserve Board, 2010).[37] The bargaining power of the entrepreneurs is set to match an aggregate capital structure target of the U.S. economy, given by the size of the (non-financial) corporate debt market relative to the market value of equity plus (non-financial) corporate debt (Fred, 2010).[38] I normalize the supply of houses and set it equal to one at the start of the model simulation. The expected idiosyncratic damages conditional on suffering losses from the climate impact, μ_L, is equal to one, as the simulation focuses on sea level rise. I target a ratio of damages to housing relative to productive capital of 0.7, which is based on Fried (2022). Finally, I set ρ equal to zero, such that the production technology is Cobb-Douglas, and the functional form of the utility of housing is $v(L) = ln(L)$.

[36] The capital share in final-good production is based on net capital share of gross domestic income, as reported by the Bureau of Economic Analysis (BEA). The net capital share is calculated as gross domestic income less consumption of fixed capital, taxes on production and imports less subsidies, less compensation of employees, divided by gross domestic income less consumption of fixed capital, taxes on production and imports less subsidies. All values are reported by the Bureau of Economic Analysis (BEA). The fraction of high-skilled labour is 0.3 and is measured as the fraction of U.S. citizens of 25 years and that have completed at least 4 years of college education. This data is provided by the U.S. Census Bureau.

[37] Data on the financial accounts of the United States for non-financial sectors is available via the Federal Reserve Board. See https://www.federalreserve.gov/releases/z1/dataviz/z1/nonfinancial_debt/table/.

[38] Data on non-financial corporate debt as a percentage of the market value of corporate equities in the United States is available via the Federal Reserve bank of St. Louis. See https://fred.stlouisfed.org/series/NCBCMDPMVCE.

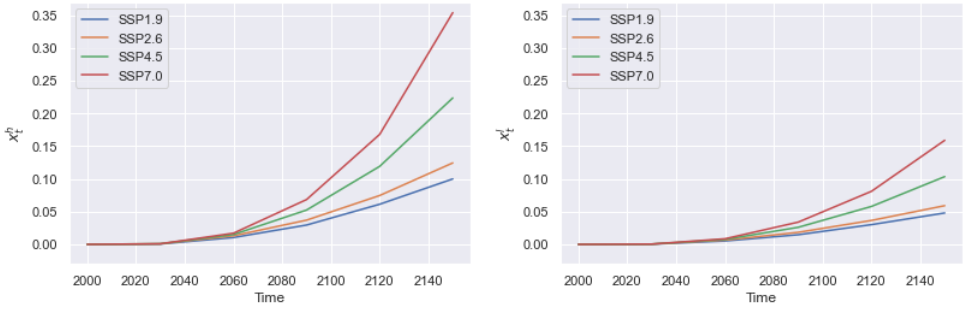

Figure 2.2: The evolution of the optimal choice of adaptation, x_t^h (left) and the constrained choice of adaptation, x_t^l,(right), under the SSP1-1.9, SSP1-2.6, SSP2-4.5 and SSP3-7.0 scenario.

2.6.3 The Evolution of Private Adaptation

To solve the model, I assume a steady state is reached by 2150, which is last year for which sea level rise projections are available. That is, I assume that climate risk remains constant after this period and solve the model backwards from this point. I compare the simulations of an economy with climate change and in which households are financially unconstrained to those of an economy where credit constraints hinder households efforts to adapt to climate change. Let left panel of Figure 2.2 shows the evolution of the optimal private choice of adaptation, x_t^h, which increases in the economy's climate risk exposure. The fraction of idiosyncratic losses which unconstrained households choose to prevent by investing in resilience rises to approximately 35 percent under the most severe climate change scenario and by the mid of the next century. At the same time, the adaptation gap widens, as becomes clear from the right panel of Figure 2.2. This panel depicts the evolution of the constrained private choice of adaptation, x_t^l, over time. Depending on the severity of the climate change scenario, the difference between the private adaptation choice of credit constrained and unconstrained households grows to 5-20 percent. Essentially, this represents the difference in the housing wealth these households protect.

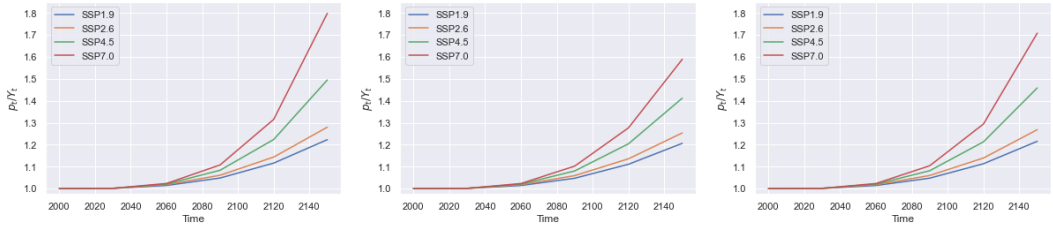

Figure 2.3: The evolution of house prices to income (indexed to 1 in 2000) under the different SSP$x-y$ scenarios, for the model with climate change only (left), the model with efficient adaptation (middle) and unequal adaptation (right) to climate change.

2.6.4 The Evolution of the House Prices

In the model, climate risk leads to an endogenous decline in the supply of inhabitable houses. Consistent with Proposition 1, this drives up house prices over time. The left panel of figure 2.3 illustrates this effect by plotting the ratio of house prices to income in the model with climate change only, which rises by approximately 50–80 percent under medium to severe climate scenarios by the middle of the next century. Adaptation moderates the decline in housing supply by allowing households to invest in damage-limiting measures, thereby weakening the scarcity effect on prices. The middle panel shows that when households adapt efficiently, the increase in the house price-to-income ratio is more moderate, rising by 40–60 percent over the same horizon. By contrast, in the unequal adaptation scenario (right panel), where not all households can preserve their housing stock effectively, the ratio still rises by approximately 45–70 percent. This highlights the aggregate importance of efficient adaptation in housing scarcity and moderating long-run price increases.

2.6.5 The Evolution of the Wealth Inequality

Credit constraints prevent low-income households from consuming the optimal amount of housing and from investing optimally in adaptation. This has implications for their accumulation of wealth. While low-income households invest less in both housing and adaptation relative to unconstrained households, they also reap relatively fewer benefits from selling the undamaged fraction of their housing due to underinvestment.

Figure 2.4: The evolution of consumption inequality due to the credit constraint channel, Δc^{λ}_{t+1} (indexed to 1 in 2000), under the different SSP$x-y$ scenarios.

Define Δc^{λ}_{t+1} as the consumption equivalent difference between the time $t+1$ capital gain on housing (i.e., the difference between the future sales price and the investment in housing) for high-income households versus low-income households. Figure 2.4 demonstrates that wealth inequality (in consumption-equivalent terms) increases due to the underinvestment channel. Specifically, consumption inequality rises by 7–8 percent under medium to severe climate scenarios by the middle of the next century due to this underinvestment.[39]

This rise in consumption-equivalent wealth inequality is entirely driven by credit constraints. Consequently, shifting from a model of constrained homeownership to a rental market with unconstrained landlords could fully offset this inequality effect. By transferring the responsibility for adaptation investments to deep-pocketed landlords, credit-constrained households are shielded from excessive climate-related housing damages. Therefore, landlord-based adaptation becomes crucial for moderating the redistributive consequences of climate change.

2.6.6 Welfare Implications

Credit constraints prevent low-income households from investing efficiently in climate adaptation. This has implications for wealth inequality, as these households lose a rel-

[39] As a reference point By comparison, the Gini coefficient –, a common measure of wealth inequality –, has risen by approximately 9.8 percent over the past 60 years. This suggests that unequal adaptation, absent adaptation, climate change could generate inequality effects over the long run that are comparable in magnitude to historical structural economic shifts.

atively larger fraction of their housing wealth upon the realization of a climate impact. It also has implications for welfare more broadly.

To assess the welfare implications of the underinvestment channel, I determine how much utility a low-income household gains per unit of housing saved through better adaptation. I define the marginal value of housing saved through adaptation as the product of the marginal utility of housing and the marginal effect of adaptation on housing preservation. This reflects the full marginal benefit of adaptation, and can be interpreted as the willingness to pay for preserving an additional unit of housing through adaptation. Panel A of Table 2.3 reports the marginal value of housing preserved through adaptation under the distinct climate change scenarios. The first row reports the marginal value in consumption equivalent units, representing the amount of consumption a household would be willing to forgo to obtain a marginal increase in the amount of preserved housing. The second row reports the same value relative to a household's consumption. Even a small increase in adaptation yield sizable welfare gains. By the mid of the next century, a household would be willing to trade up to 11.7 percent of their consumption (or 13.4 percent of their income) for a marginal increase in preserved housing. The fourth row expresses the value of saved housing as a fraction of the market value of the entire home. This share rises from 4.7 to 17.9 percent, reflecting the increasing benefits of adaptation in more severe climate futures.

To quantify the inefficiency caused by credit constraints, I further compute how much better off a household would be if it could adapt at the optimal (unconstrained) level rather than at the constrained private level. This reflects the utility cost of the underinvestment in adaptation.[40] I define the utility cost of housing lost through the underinvestment

[40] Note that unlike the marginal value of housing saved through adaptation (which is a marginal response) - this is the stock loss across the whole difference in outcomes.

	SSP1–1.9	SSP1–2.6	SSP2–4.5	SSP3–7.0
A. Marginal value of housing *saved* through adaptation				
Consumption equivalent	0.038	0.047	0.083	0.127
Relative to consumption (%)	3.690	4.509	7.724	11.726
Relative to income (%)	3.971	4.909	8.679	13.393
Relative to house value (%)	4.464	5.641	10.731	17.921
B. Utility cost of housing *lost* through the underinvestment				
Consumption equivalent	0.002	0.003	0.010	0.0247
Relative to consumption (%)	0.192	0.295	0.929	2.288
Relative to income (%)	0.207	0.321	1.044	2.613
Relative to house value (%)	0.232	0.369	1.290	3.497

Table 2.3: Marginal value of adaptation.

in adaptation as the product of the marginal utility of housing and the forgone housing preservation due to the sub-optimal adaptation choice.[41] Panel B of Table 2.3 reports the utility cost of housing lost through the underinvestment in adaptation under the distinct climate change scenarios. The utility cost of lost housing, relative to consumption, reaches up to 2.3 percent (or 2.6 percent relative to income) under the most severe climate scenario. This indicates that constrained households lose out in aggregate, as they are systematically unable to invest the optimal amount in adaptation. The corresponding loss amounts to up to 3.5 percent of the market value of the home. Taking into account the mean home value in the Miami-area[42] and the model-implied rise in house prices, this implies a welfare loss of approximately $15,700 per household per housing unit. This highlights the long-term implications of constrained adaptation and signals the benefits of improving access to finance or switching to landlord-driven adaptation.

Taken together, these results demonstrate the growing value of climate change adap-

[41] Note that this approximates the utility costs linearly.

[42] I use the Zillow Home Value Index (ZHVI), which captures the typical home value across housing types within a region, focusing on homes in the 35th to 65th percentile range. Specifically, I use the smoothed, seasonally adjusted ZHVI for all homes at the county level. In line with the focus of the model simulation on the Miami area, I focus on the Miami-Dade County. To abstract from short-term volatility unrelated to climate change, I compute the average ZHVI over the 2000–2024 period using year-end values. This yields a base home value of 271,423.40 US dollars.

tation as well as the costs of inaction. Importantly, these costs are not evenly distributed: they fall disproportionately on credit-constrained households, who are unable to finance efficient adaptation. As climate risks rise, unequal access to adaptation finance leads to rising welfare inequality.

2.7 Model Extension: Insurance Markets

Insurance plays a key role in mitigating the impact of climate change on household wealth, since households can privately insure climate related damages to their home with home insurance. In the context of climate change, a challenge arises as multiple households face similar climate-related risks, leading to the correlation of losses. This complicates the insurance landscape.

2.7.1 Institutional Context

In Florida, homeowners are not legally required to have flood insurance. However, mortgage lenders often require it to protect against the risk of physical damage to the property that serves as collateral, as this could lead to a decline in its value.[43] Government-backed lenders further mandate flood insurance for properties located in areas designated as "Special Flood Hazard Areas" by the Federal Emergency Management Agency (FEMA).[44] Flood damage, caused by storms, heavy rain, or overflowing water bodies, are typically not covered by home insurance policies. Therefore, homeowners who live in a flood zone must obtain separate flood insurance.

Flood insurance is offered through the National Flood Insurance Program (NFIP), a federally-backed initiative administered by the government for homeowners, renters, and businesses. Eligibility for NFIP coverage depends on the property's flood zone and the community's participation in the program. The NFIP covers physical damages directly caused by flooding, up to a limit of 250,000 US dollars for building coverage.

[43] For simplicity, I do not model any relation between the insurance and mortgage contract.

[44] FEMA's flood maps are regularly updated. Consequently, many areas are being reclassified over time.

In Florida, the average annual cost of NFIP flood insurance is 760 US dollars, and the average claim payout is approximately 29,000 US dollars. Homeowners can also apply for FEMA disaster assistance in addition to an insurance claim. This is available only for properties in areas that have received a Presidential Disaster Declaration.[45] The average FEMA disaster relief payment in Florida is about 5,100 US dollars. Additional flood coverage is available through private insurers. However, private insurance providers are increasingly exiting the Florida market due to the high risks associated with climate change (Sastry et al., 2023; Nicholson, Born, Cole, and Nyce, 2020). Also Citizens, a state-backed insurer of last resort for those who cannot find affordable coverage through private insurers, potentially brings forward a role for the state in providing coverage as private options fail, does not provide flood insurance.[46]

2.7.2 Climate Risk Insurance

Households may insure damages to their housing capital at the time of purchase. Insurance is provided by insurance intermediaries, which are owned by households. Denote by $\pi_{i,t} \in [0, 1]$ the amount of coverage (per unit of housing capital, $L_{i,t}$) chosen by household i, at time t. Thus, $\pi_{i,t} = 1$ indicates that the household purchases full coverage for insured losses, while $\pi_{i,t} < 1$ indicates that the household chooses fractional coverage. Private insurance has empirically become increasingly less available, with private insurers exiting the market or limiting the value of losses covered. (Sastry et al., 2023; Boomhower et al., 2024).[47] Since multiple households face similar climate-related risks, and losses thus are correlated, providing coverage will become increasingly challenging as climate risks continue to rise.

The expected payout that insured households receive per unit of housing capital

[45] Homeowners in flood zones who have previously received federal disaster aid are required to maintain flood insurance to remain eligible for future aid.

[46] Citizens is gradually introducing flood insurance requirements for its home insurance customers. Specifically, in 2023, customers in high-risk flood zones were required to have flood insurance, regardless of mortgage status. By January 2027, all Citizens home insurance customers will need to have flood insurance.

[47] Sastry et al. (2023) documents this in the context of flood risk and Boomhower et al. (2024) for wildfire risk.

insured equals the future price times the expected losses covered within the insurance limit, i.e., $\mathbb{E}\left(\xi_{i,t+1}\right) \cdot p_{t+1}$. Insurers have perfect foresight on the climate risk exposure of the economy, and on future house prices since there is no aggregate uncertainty. However, since it is prohibitively costly to verify individual households' private adaptation choices (see Section V.D.), insurance intermediaries also form expectations on the choice of adaptation of a given household, denoted by $\mathbb{E}\left(\bar{x}_{i,t}\right)$. Denote the insurance premium for full coverage by z_t. Insurance is actuarially priced, that is, the premium reflects the discounted expected payout per unit of housing capital insured.[48] [49] Then, the insurance premium is given by

$$z_t = \frac{(1 - \mathbb{E}(\bar{x}_{i,t}))\mu\gamma_{t+1} \cdot p_{t+1}}{(1+r)}$$

The rise in climate risk leads to larger expected damages. Simultaneously, the rise in house prices increases the value of the insured asset. This increases the expected payout, raising insurance premia over time.[50]

2.7.3 Optimal Demand for Adaptation with Insurance

Since households are risk-neutral with respect to their consumption of the non-durable good, there is no demand for insurance, i.e., $\pi^*_{i,t} = 0$. Nevertheless, even without a strictly positive demand for insurance, the implication of insurance on house prices and the private choice of adaptation can be studied – which is the main purpose of this model extension. When households can insure the losses due to flooding, the house-

[48] Since insurance is actuarially fair, premia simply reflect each household's expected losses, thus leaving no net transfer across the system in expectation.

[49] In the U.S., insurance premia are heavily subsidized, preventing full risk pricing. This is also the case in government-provided insurance programs as the NFIP. This provides an implicit subsidy to homeowners living in high risk areas and hinders price signals. While I abstract from mispricing in this framework, this would strengthen the moral hazard effect and further reduce investments in adaptation.

[50] This is already unfolding in real time. Keys and Mulder (2024) study homeowner insurance and document an increase in the average insurance premium between 2020-2023, which is the result of a stronger relationship between premiums and local disaster risk.

hold maximization problem is given by:

$$\begin{aligned}
\max_{c_{i,t+1},L_{i,t},S_{i,t},x_{i,t},\pi_{i,t}} \quad & \mathbb{E}_t\left(c_{i,t+1}\right) + v(L_{i,t}) \\
s.t. \quad y_{i,t} &\leq \left(p_t + z_t\pi_{i,t} + \frac{1}{2}x_{i,t}^2\right) L_{i,t} + \ + S_{i,t} \\
c_{i,t+1} &\leq \max\left\{p_{t+1}(1-(1-\pi_{i,t})\tilde{\xi}_{i,t+1})L_{i,t} + (1+\hat{r})S_{i,t}, 0\right\} \\
c_{i,t+1}, L_{i,t}, x_{i,t}, \pi_{i,t} &\geq 0.
\end{aligned}$$

Lemma 5. *When households can insure against losses due to flooding, the optimal private choice of adaptation is given by:*

$$x_{i,t} = \frac{(1-\pi_{i,t}) \cdot \mu_L \gamma_{t+1} \cdot p_{t+1}}{(1+r)}$$

Climate risk insurance leads to moral hazard in adaptation. Due to the non-verifiability of the private efforts undertaken, insurance allows households to limit the downside from a disaster in a relatively cheaper way than by investing in adaptation. Specifically, the marginal costs of insurance are constant, while the marginal costs of adaptation - which is an increasingly costly investment as one wants to prevent a larger fraction of damages - are rising. Hence, as households do not bear the full consequences of their action any longer, insurance provision reduces households' willingness to undertake adaptation investments. The private adaptation investment falls by a fraction $\pi_{i,t}$ in response. That is, households invest in adaptation to mitigate *uninsured* damages to their housing only. In the case of full coverage and without any insurance limit, this means that households do not invest in adaptation at all, and rather rely on insurance to provide compensation for damages after they occur.

The choice of insurance is not separable from their adaptation (Mayers and Smith Jr, 1983), however, since insurance coverage affects the price of the insured good. That is, even though the premium is actuarial, insurance provision affects the price of housing capital the general equilibrium.

Lemma 6. *When households can insure against losses due to flooding, the price of housing*

capital is given by:

$$p_{t+1} = \sum_{j=t+1}^{\infty} \left(\frac{1}{1+r}\right)^{j-(t+1)} \left[-(1+r)\left(z_j \pi_j + \frac{1}{2}x_j^2\right) + v'(\bar{L}_j)\right] \cdot \prod_{i=t+1}^{j-1} (1-(1-\pi_i)(1-x_i)\mu\gamma_{i+1})$$

where $\pi_t = \int_0^1 \pi_{i,t} di$.

The provision of insurance reduces incentives for households to invest in adaptation, leading to a faster reduction in the housing supply. This accelerates the rise in house prices. As households' adaptation choices depend on house prices — which reflect the value at risk — the "home equity effect" provides a countervailing force against the moral hazard effect. However, as there is moral hazard in the first place, the home equity effect never dominates in equilibrium. More specifically, this is because the elasticity of future house prices with respect to the choice of insurance remains less than unity. Therefore, climate risk insurance provision crowds out private adaptation. Figure 2.5 illustrates this over time.

Proposition 6. The provision of climate risk insurance crowds out private adaptation.

Proof: See Appendix A.6

While encouraging partial coverage (i.e., altering quantities) could reduce moral hazard (Stiglitz and Weiss, 1981), a trade-off emerges between reducing inequality across generations and reducing inequality within generations. While a higher coverage would reduce the redistributive effects of climate change *within* generations due to the monetary compensation provided for damages, the moral hazard in adaptation discourages investments in resilience to climate risks when coverage is too high, which increases wealth inequality *across* generations. This has implication for the optimal design of climate risk insurance, which should account for its distributional consequences - both across and within generations. Policymakers must carefully balance this trade-off in designing effective insurance schemes.

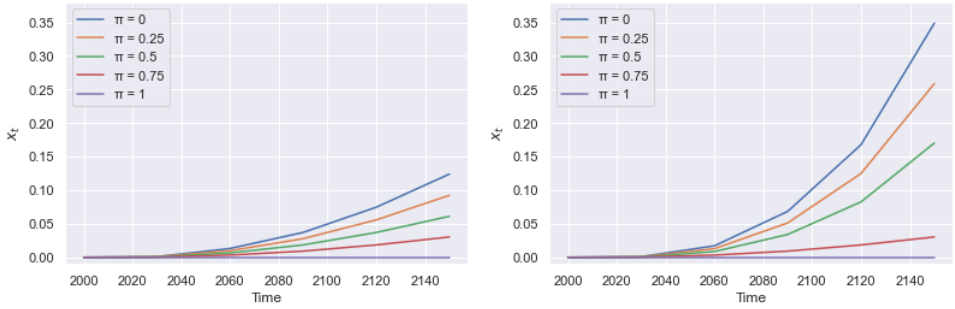

Figure 2.5: The evolution of the private choice of adaptation, x_t, for various choices of insurance coverage, π, under SSP2-4.5 (left) and SSP3-7.0 (right).

2.8 Conclusion

This paper explores the broader macro-financial implications of climate change and adaptation, by embedding climate risk in a general equilibrium framework. Households are exposed to physical climate risks, which damage the housing - and degrades land. While the exposure to climate risk weakens demand for housing, I show that the materialization of climate change raises house prices, as habitat becomes increasingly scarcer. This leads to an rise in household debt and a reallocation of credit in the economy towards households.

I analyze the changing incentives of households to invest in climate change adaptation against the backdrop of rising climate risk. Although in frictionless markets price signals lead to efficient adaptation, credit-constrained households have weaker incentives to adapt to climate change, indicating that pricing alone may be insufficient. This reinforces wealth inequality and leads to a further reduction in future habitat. Due to this rising scarcity, housing becomes increasingly important in the consumption bundle. This further weakens the incentives of credit constrained households to invest in future resilience, leading to a widening of the private adaptation gap over time. Credit constraints present a significant challenge to effective climate adaptation (IPCC, 2023; Havlinova et al., 2022) necessitating targeted policies to address the differential impacts of climate change. One such policy is to encourage credit constraint households to rent rather than buy housing. I demonstrate that a societal shift from constrained home-

ownership to a rental model with unconstrained owners could lead to more efficient adaptation.

The results in this paper indicate that low-income households do not need to live in a riskier area to be more exposed to climatic impacts. A potential limitation of the analysis is that migration is not considered. Cruz and Rossi-Hansberg (2024); Bilal and Rossi-Hansberg (2023); Desmet and Rossi-Hansberg (2015); Muis et al. (2015). Sastry (Forthcoming) show that migration is a key adaptation mechanism, as it reduces substantially the welfare impact of climate change. However, migration is costly (Desmet and Rossi-Hansberg, 2015). Therefore, migrating only offers an alternative to investing in self-protective measures to those who are able to afford it.[51] The model may also speak to this. Imagine that, instead of investing in adaptation, households could choose their home's distance from the coast. If relocating further inland entails a convex adjustment cost, the migration decision would resemble the adaptation decision, leading to under-migration by credit-constrained households. Unlike adaptation, migration would only reduce households' expected property damages without affecting the overall rate of land degradation. This distinction underscores the significant role of adaptation in slowing the loss of habitable land, whereas migration merely reallocates exposure to risk.

Finally, this paper focused on analyzing household incentives to adapt to climate change, while abstracting from mitigation strategies. Given the non-linear nature of climate change, it is important to recognize that adaptation alone cannot completely prevent potentially large economic losses (see also Bilal and Rossi-Hansberg, 2023). Indeed, the extent to which we succeed in mitigating climate change directly affects the necessity for adaptation measures. Adaptation and mitigation strategies both involve substantial costs. Thus, a trade-off between these may emerge, especially when decisions are made when financial resources are scarce. The interplay between adaptation and mitigation strategies is left as avenue for future research.

[51] Varela Varela (2023) shows that post-flood migration patterns reinforce neighborhood segregation, thus increasing preexisting spatial inequities.

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Appendix

2.10 Proof of Propositions

2.10.1 Proof of Proposition 1

Suppose climate risk rises in all future periods by some factor $\sigma > 1$, i.e. $\{\sigma\gamma_{t+1}, ..., \sigma\gamma_\infty\}$. Then, the price of house capital is given by

$$p_t^* = \sum_{j=t}^{\infty} \left(\frac{1}{1+r}\right)^{j-t+1} \left[v'\left(\bar{L}_j\right)\right] \prod_{\iota=t}^{j-1} (1 - \mu_L \sigma \gamma_{\iota+1})$$

Then, the FOC of p_t with respect to σ is given by

$$\frac{\partial p_t}{\partial \sigma} = \sum_{j=t}^{\infty} \left(\frac{1}{1+r}\right)^{j-t+1} \left[\frac{\partial v'(\bar{L}_j)}{\partial \bar{L}_j} \cdot \frac{\partial \bar{L}_j}{\partial \sigma} \cdot \prod_{\iota=t}^{j-1}(1 - \mu_L \sigma \gamma_{\iota+1}) + v'\left(\bar{L}_j\right) \cdot \frac{\partial}{\partial \sigma}\left(\prod_{\iota'=t}^{j-1}(1 - \mu_L \sigma \gamma_{\iota'+1})\right)\right]$$

Remark that

$$\bar{L}_j = \bar{L}_t \prod_{\iota=t}^{j-1} (1 - \mu_L \sigma \gamma_{\iota+1})$$

and

$$\frac{\partial \bar{L}_j}{\partial \sigma} = -\mu_L \bar{L}_t \sum_{\iota=t}^{j-1} \gamma_{\iota+1} \prod_{\iota'=t, \iota' \neq \iota}^{j-1} (1 - \mu_L \sigma \gamma_{\iota'+1})$$

then

$$\frac{\partial p_t}{\partial \sigma} = \sum_{j=t}^{\infty} \left(\frac{1}{1+r}\right)^{j-t+1} \left[-\frac{\partial v'(\bar{L}_j)}{\partial \bar{L}_j} \cdot \bar{L}_j - v'\left(\bar{L}_j\right)\right] \cdot \mu_L \sum_{\iota=t}^{j-1} \gamma_{\iota+1} \prod_{\iota'=t, \iota' \neq \iota}^{j-1} (1 - \mu_L \sigma \gamma_{\iota'+1})$$

This is positive if

$$-\frac{\partial v'(\bar{L}_j)}{\partial \bar{L}_j} \cdot \bar{L}_j - v'\left(\bar{L}_j\right) \geq 0$$

or, equivalently if

$$-\frac{\frac{\partial v'(\bar{L}_j)}{\partial \bar{L}_j} \cdot \bar{L}_j}{v'\left(\bar{L}_j\right)} \geq 1$$

2.10.2 Proof of Proposition 2

The unconstrained social planner maximizes utilitarian welfare, i.e.

$$\max_{x_t} \sum_{t=0}^{\infty} \left(\frac{1}{1+r}\right)^t \left[-\frac{1}{2}(1+r)\bar{L}_t \cdot x_t^2 + v(\bar{L}_t)\right]$$

subject to

$$\bar{L}_j = \bar{L}_t \prod_{\iota=t}^{j-1} (1-(1-x_\iota)\mu_L \gamma_{\iota+1})$$

The first order condition for x_t is

$$\left(\frac{1}{1+r}\right)^t \cdot (1+r)x_t \cdot \bar{L}_t = \sum_{j=t+1}^{\infty} \left(\frac{1}{1+r}\right)^j \left[-(1+r)\frac{1}{2}x_j^2 + v'(\bar{L}_j)\right] \frac{\partial \bar{L}_j}{\partial x_t}$$

Using that

$$\frac{\partial \bar{L}_j}{\partial x_t} = \mu_L \gamma_{t+1} \cdot \bar{L}_t \prod_{\iota=t+1}^{j-1} (1-(1-x_\iota)\mu_L \gamma_{\iota+1})$$

this becomes

$$(1+r)x_t = \mu_L \gamma_{t+1} \sum_{j=t+1}^{\infty} \left(\frac{1}{1+r}\right)^{j-t} \left[-(1+r_{j+1})\frac{1}{2}x_j^2 + v'(\bar{L}_j)\right] \prod_{\iota=t+1}^{j-1} (1-(1-x_\iota)\mu_L \gamma_{\iota+1})$$

The first-order condition of the unconstrained household is

$$(1+r)x_t = \mu_L \gamma_{t+1} \cdot p_{t+1}$$

and the first-order condition of the unconstrained social planner is

$$(1+r)x_t = \mu_L \gamma_{t+1} \sum_{j=t+1}^{\infty} \left(\frac{1}{1+r}\right)^{j-t} \left[-\frac{1}{2}(1+r)x_j^2 + v'(\bar{L}_j)\right] \prod_{\iota=t+1}^{j-1} (1-(1-x_\iota)\mu_L \gamma_{\iota+1})$$

A necessary and sufficient condition for the privately optimal level of investment to be efficient is

$$p_{t+1} = \sum_{j=t+1}^{\infty} \left(\frac{1}{1+r}\right)^{j-t} \left[-\frac{1}{2}(1+r)x_j^2 + v'(\bar{L}_j)\right] \prod_{\iota=t+1}^{j-1} (1-(1-x_\iota)\mu_L \gamma_{\iota+1})$$

which holds. Therefore, under the condition that the social planner discounts the welfare of future generations using the market-implied discount rate, the first-order condition of the unconstrained social planner is equivalent to the first-order condition of the unconstrained household. This implies that the market outcome is efficient.

2.10.3 Proof of Proposition 3

The first-order condition for L_l^* is derived from the constrained household problem as

$$-(1+r)(1+\lambda)\left(\frac{1}{2}x_{l,t}^{*,2}(\lambda) + p_t\right) + (1+\lambda)\left(1-\left(1-x_{l,t}^*\right)\mu_L\gamma_{t+1}\right)p_{t+1} + v'\left(L_{l,t}^*\right) = 0$$

This condition defines an implicit expression for λ_t, i.e.

$$\lambda_t = \frac{\left(1-\left(1-x_{l,t}^*(\lambda_t)\right)\mu_L\gamma_{t+1}\right)p_{t+1} + v'\left(L_{l,t}^*\right) - (1+r)\left(\frac{1}{2}x_{l,t}^{*,2}(\lambda_t) + p_t\right)}{(1+r)\left(\frac{1}{2}x_{l,t}^{*,2}(\lambda_t) + p_t\right) - p_{t+1}\left(1-\left(1-x_{l,t}^*(\lambda_t)\right)\mu\gamma_{t+1}\right)}$$

Since λ_t denotes the change in the optimal level of utility for loosening the constraint

by one unit, it holds by construction that $\lambda_t \geq 0$. What remains to be determined, is under which condition $\lambda_t = 0$.

As the denominator is strictly positive, the following condition must hold:

$$p_t = \frac{\left(1 - \left(1 - x^*_{l,t}(0)\right)\mu_L \gamma_{t+1}\right) p_{t+1} + v'\left(L^*_{l,t}\right)}{1+r} - \frac{1}{2} x^{*,2}_{l,t}(0)$$

In this case, $\lambda_t = 0 \implies x^*_{l,t} = x^*_{h,t}$. Recall that the price of housing capital is defined as

$$p_t = \frac{\left(1 - (1 - x^*_{h,t})\mu_L \gamma_{t+1}\right) p_{t+1} + v'\left(L^*_{h,t}\right)}{1+r} - \frac{1}{2} x^{*,2}_{h,t}$$

Then, a necessary and sufficient condition for the above condition to hold is that $v'\left(L^*_{l,t}\right) = v'\left(L^*_{h,t}\right)$. This implies that $L^*_{l,t} = L^*_{h,t}$, which can only hold if the constraint doesn't bind. However, in the presence of binding credit constraints, $L^*_{l,t} < L^*_{h,t} \implies v'\left(L^*_{l,t}\right) > v'\left(L^*_{h,t}\right)$. By contradiction, it must then be the case that $\lambda_t > 0$.

2.10.4 Proof of Proposition 4

To evaluate the effect of a rise in γ_{t+1} on λ_t, the expression for λ_t is first rewritten as:

$$(1 + \lambda_t) = \frac{v'\left(L^*_{l,t}\right)}{v'\left(L^*_{h,t}\right) + \frac{1}{2}(1+r) \cdot x^{*2}_{l,t}(\lambda_t) \cdot \lambda_t^2}$$

Then, the FOC becomes

$$\frac{\partial \lambda_t}{\partial \gamma_{t+1}} = \frac{\frac{\partial v'\left(L^*_{l,t}\right)}{\partial L^*_{l,t}} \cdot \frac{\partial L^*_{l,t}}{\partial \gamma_{t+1}} \cdot \left[v'\left(L^*_{h,t}\right) + \frac{1}{2}(1+r) \cdot x^{*2}_{l,t} \cdot \lambda_t^2\right]}{\left(v'\left(L^*_{h,t}\right) + \frac{1}{2}(1+r) \cdot x^{*2}_{l,t}(\lambda_t) \cdot \lambda_t^2\right)^2}$$

$$- \frac{v'\left(L^*_{l,t}\right) \cdot \left[\frac{\partial v'\left(L^*_{h,t}\right)}{\partial L^*_{h,t}} \cdot \frac{\partial L^*_{h,t}}{\partial \gamma_{t+1}} + (1+r) \cdot \left(\frac{\partial x^*_{l,t}}{\partial \lambda_t} \cdot \frac{\partial \lambda_t}{\partial \gamma_{t+1}} \cdot x^*_{l,t} \lambda_t^2 + x^{*2}_{l,t} \lambda_t \cdot \frac{\partial \lambda_t}{\partial \gamma_{t+1}}\right)\right]}{\left(v'\left(L^*_{h,t}\right) + \frac{1}{2}(1+r) \cdot x^{*2}_{l,t}(\lambda_t) \cdot \lambda_t^2\right)^2}$$

This FOC is positive if

$$\frac{\partial \lambda_t}{\partial \gamma_{t+1}} \left[1 + v'\left(L^*_{l,t}\right) \cdot (1+r) \cdot \left(\frac{\partial x^*_{l,t}}{\partial \lambda_t} \cdot x^*_l \cdot \lambda_t^2 + x^{*2}_{l,t} \cdot \lambda_t \right) \right] \geq$$
$$\frac{\partial v'\left(L^*_{l,t}\right)}{\partial L^*_{l,t}} \cdot \frac{\partial L^*_{l,t}}{\partial \gamma_{t+1}} \cdot \left[v'\left(L^*_{h,t}\right) + \frac{1}{2}(1+r) x^{*2}_{l,t} \cdot \lambda_t^2 \right] - v'\left(L^*_{l,t}\right) \cdot \left[\frac{\partial v'\left(L^*_{h,t}\right)}{\partial L^*_{h,t}} \cdot \frac{\partial L^*_{h,t}}{\partial \gamma_{t+1}} \right]$$

Using that

$$\frac{\partial x^*_{l,t}}{\partial \lambda_t} = -\frac{x^*_{l,t}}{(1+\lambda_t)}$$

the LHS is rewritten

$$\frac{\partial \lambda_t}{\partial \gamma_{t+1}} \underbrace{\left[1 + \lambda_t \cdot v'\left(L^*_{l,t}\right) \cdot (1+r) \cdot x^2_{l,t} \cdot \left(1 - \frac{\lambda_t}{(1+\lambda_t)} \right) \right]}_{\geq 0}$$

which is positive. Hence, the RHS remains to be evaluated. The RHS is rewritten as

$$\underbrace{\frac{\partial v'\left(L^*_{l,t}\right)}{\partial L^*_{l,t}}}_{\leq 0} \cdot \underbrace{\frac{\partial L^*_{l,t}}{\partial \gamma_{t+1}}}_{\leq 0} \cdot \underbrace{\frac{1}{v'\left(L^*_{l,t}\right)}}_{\geq 0} - \underbrace{\frac{\partial v'\left(L^*_{h,t}\right)}{\partial L^*_{h,t}}}_{\leq 0} \cdot \underbrace{\frac{\partial L^*_{l,t}}{\partial \gamma_{t+1}}}_{\leq 0} \cdot \underbrace{\frac{1}{v'\left(L^*_{h,t}\right)}}_{\geq 0} + \underbrace{\frac{\left(\frac{1}{2}(1+r_{t+1}) x^{*2}_{l,t} \lambda_t^2\right)}{v'\left(L^*_{h,t}\right)}}_{\geq 0} \cdot \underbrace{\frac{\partial v'\left(L^*_{l,t}\right)}{\partial L^*_{l,t}}}_{\leq 0} \cdot \underbrace{\frac{\partial L^*_{l,t}}{\partial \gamma_{t+1}}}_{\leq 0} \cdot \underbrace{\frac{1}{v'\left(L^*_{l,t}\right)}}_{\geq 0}$$

Then, in order for $\partial \lambda_t / \partial \gamma_{t+1}$ to be positive, it must hold that

$$\frac{\partial v'\left(L^*_{l,t}\right)}{\partial L^*_{l,t}} \cdot \frac{\partial L^*_{l,t}}{\partial \gamma_{t+1}} \cdot \frac{1}{v'\left(L^*_{l,t}\right)} - \frac{\partial v'\left(L^*_{h,t}\right)}{\partial L^*_{h,t}} \cdot \frac{\partial L^*_{l,t}}{\partial \gamma_{t+1}} \cdot \frac{1}{v'\left(L^*_{h,t}\right)} \geq 0$$

Suppose the utility function is characterized by CRRA with relative risk aversion coefficient ς. Then, the expression becomes

$$-\varsigma \left(\underbrace{\frac{\partial L^*_{l,t}}{\partial \gamma_{t+1}}}_{\leq 0} \cdot \frac{1}{L^*_{l,t}} - \underbrace{\frac{\partial L^*_{h,t}}{\partial \gamma_{t+1}}}_{\leq 0} \cdot \frac{1}{L^*_{h,t}} \right) \geq 0$$

which holds as the elasticity of the demand for housing of credit constrained, low-income households is larger than the elasticity for housing of unconstrained households in the presence of binding financial constraints. In conclusion, λ_t rises in γ_{t+1} if the utility function for housing is characterized by CRRA with RRA coefficient ς.

2.10.5 Proof of Proposition 5

If the rental market is perfectly competitive, it must be that (unconstrained) households are indifferent between renting and buying, i.e.

$$\mathbb{E}(U(\text{buy})) = -\left(p_t + \frac{1}{2}{x_{i,t}}^2\right) \cdot L_{i,t} + \frac{(1-(1-x_{i,t})\mu_L\gamma_{t+1})\, p_{t+1} \cdot L_{i,t}}{(1+r)} + v(L_{i,t}) =$$
$$\mathbb{E}(U(\text{rent})) = v\left(L_{i,t}\right) - \mathrm{Y}_t \cdot L_{i,t}$$

with Y_t the rental price price per unit of housing capital. This gives:

$$\mathrm{Y}_t = \left(p_t + \frac{1}{2}{x_{i,t}}^2\right) - \frac{(1-(1-x_{i,t})\mu_L\gamma_{t+1})\, p_{t+1}}{(1+r)}$$

Recall that with adaptation, the house price is given by

$$p_t + \frac{1}{2}{x_t}^2 = \frac{(1-(1-x_t)\mu_L\gamma_{t+1})\, p_{t+1} + v'(\bar{L}_t)}{(1+r)}$$

where $\bar{L}_t = \int_0^1 L^*_{i,t} di$ and $x_t = \int_0^1 x^*_{i,t} di$. Hence, the rental price per unit of housing capital is given by:

$$\mathrm{Y}_t = v'(\bar{L}_t)$$

The investment in adaptation is purely driven by financial motives. Hence, landlords have the incentive to invest optimally in adaptation, i.e.

$$x^*_{i,t} = \frac{\mu_L\gamma_{t+1} \cdot p_{t+1}}{(1+r)}$$

Consequently, if credit constrained households rent, the optimal investment in adaptation is made for all houses in the economy, not just those owned by unconstrained household.

Since the probability of being hit by the flood is i.i.d. across households, unconstrained households remain equally well-off in expectation when they become landlords, i.e.

$$\mathbb{E}(U_h(\text{landlord})) = \mathbb{E}(U_h(\text{no landlord}))$$

where

$$\mathbb{E}(U_h(\text{landlord})) = 2\left[-\left(p_t + \frac{1}{2}{x_{i,t}}^{*2}\right)\cdot L_t^* + \frac{\left(1-(1-x_{i,t}^*)\mu_L\gamma_{t+1}\right)p_{t+1}\cdot L_t^*}{(1+r)}\right] + v(L_t^*) + \text{Rent}\cdot L_t^*$$

$$\mathbb{E}(U_h(\text{no landlord})) = -\left(p_t + \frac{1}{2}{x_{i,t}}^{*2}\right)\cdot L_t^* + \frac{\left(1-(1-x_{i,t}^*)\mu_L\gamma_{t+1}\right)p_{t+1}\cdot L_t^*}{(1+r)} + v(L_t^*)$$

Finally, constrained households are better off if they rent, as this allows them to consume the optimal level of housing capital:

$$\mathbb{E}(U_l(\text{rent})) = -\left(p_t + \frac{1}{2}{x_{i,t}}^{2*}\right)\cdot L_t^* + \frac{\left(1-(1-x_{i,t}^*)\mu_L\gamma_{t+1}\right)p_{t+1}\cdot L_t^*}{(1+r)} + v(L_t^*)$$

This gives them a higher than in the case in which they buy housing (see Proof of Proposition 3):

$$\mathbb{E}(U_l(\text{buy})) = -\left(p_t + \frac{1}{2}{x_{l,t}}^{2}\right)\cdot L_{l,t} + \frac{(1-(1-x_{l,t})\mu_L\gamma_{t+1})\,p_{t+1}\cdot L_{l,t}}{(1+r)} + v(L_{l,t})$$

2.10.6 Proof of Proposition 6

Future house price rises in choice of insurance if and only if insurance accelerates the rate at which the housing stock falls:

$$\frac{\partial p_{t+1}}{\partial \pi_t} = \sum_{j=t+1}^{\infty} \left(\frac{1}{1+r}\right)^{j-(t+1)} \left[\underbrace{\frac{\partial v'(\bar{L}_j)}{\partial \bar{L}_j}}_{<0} \cdot \frac{\partial \bar{L}_j}{\partial \pi_t}\right] \cdot \prod_{i=t+1}^{j-1} \underbrace{(1-(1-\pi_i)(1-x_i)\mu_L \gamma_{i+1})}_{>0}$$

which requires that

$$\frac{\partial \bar{L}_j}{\partial \pi_t} = \bar{L}_t \cdot \sum_{i=t}^{j-1} \mu_L \gamma_{i+1} \left(\frac{\partial x_i}{\partial \pi_t}\right) \prod_{i'=t, i' \neq i}^{j-1} \underbrace{(1-(1-x_{i'})\mu_L \gamma_{i'+1})}_{>0} < 0$$

where

$$\frac{\partial x_t}{\partial \pi_t} = -\frac{\mu_L \gamma_{t+1} p_{t+1}}{(1+r)} + \frac{(1-\pi_t)\mu_L \gamma_{t+1}}{(1+r)} \cdot \frac{\partial p_{t+1}}{\partial \pi_t}$$

For this derivative to be negative, it must be that the elasticity of future house prices, p_{t+1} with respect to the choice of insurance, π_t is less than unity, i.e.

$$\frac{\partial p_{t+1}}{\partial \pi_t} \cdot \frac{1}{p_{t+1}} < 1$$

Suppose this condition does *not* hold. Then, insurance fosters private adaptation, i.e., $\frac{\partial x_t}{\partial \pi_t} > 0$, which implies that insurance reduces the rate at which the housing supply falls, i.e., $\frac{\partial \bar{L}_j}{\partial \pi_t} > 0$. Then, since the supply of housing falls at a slower rate, it must be that $\frac{\partial p_{t+1}}{\partial \pi_t} < 0$.

However, this implies that the home equity effect is negative. Consequently, the choice of adaptation must fall in the choice of insurance, i.e., $\frac{\partial x_t}{\partial \pi_t} < 0$. This implies that the supply of housing falls at a faster rate, i.e., $\frac{\partial \bar{L}_j}{\partial \pi_t} < 0$, which is a contradiction. Hence, demand for insurance crowds out private adaptation.

2.10.7 Proof of Proposition 7

Wage inequality increases with climate-related damages when

$$\frac{\partial \left(q_t/w_t\right)}{\partial \gamma_t} = \frac{\eta}{(1-\eta)} \cdot \left(\frac{(1-\phi)\tilde{l})}{\phi \tilde{h}}\right)^{1-(1-\alpha)\rho} \cdot \frac{\partial}{\partial \gamma_t}\left(\frac{H_t}{(1-\mu_K \gamma_t)\, K_t}\right)^{\alpha\rho} \geq 0$$

For this to hold, it must be that

$$\frac{\mu_K}{(1-\mu_K\gamma_t)} + \frac{\partial H_t/\partial \gamma_t}{H_t} - \frac{\partial K_t/\partial \gamma_t}{K_t} \geq 0$$

or equivalently

$$\frac{\mu_K}{(1-\mu_K\gamma_t)} \geq \frac{\partial}{\partial \gamma_t} ln\left(\frac{K_t}{H_t}\right)$$

Hence, the losses of tangible capital (*i.e. the direct effect*) must be larger than the change in the investment in tangible capital relative to the investment in intangible capital in response to climate-related damages *(i.e. the indirect effect)*. To proof this, it suffices to show that

$$\frac{\partial}{\partial \gamma_t} ln\left(\frac{K_t}{H_t}\right) \leq 0$$

Note first that

$$H_t = I^*_{t-1} = \omega \cdot A^\rho \alpha\eta \cdot \frac{Y_t{}^{(1-\rho)}}{H_t^{1-\alpha\rho}} \cdot h_t^{(1-\alpha)\rho}$$

Using logarithmic differentiation, the derivative of H_t to γ_t becomes

$$(2-\alpha\rho)\frac{\partial}{\partial \gamma_t} ln(H_t) = (1-\rho)\frac{\partial}{\partial \gamma_t} ln(Y_t)$$

The derivative of Y_t to γ_t is given by

$$\begin{aligned}\frac{\partial}{\partial \gamma_t} Y_t &= \frac{\partial Y_t}{\partial H_t} \cdot \frac{\partial H_t}{\partial \gamma_t} + \frac{\partial Y_t}{\partial K_t} \cdot \frac{\partial K_t}{\partial \gamma_t} \\ &= R_t \cdot \frac{\partial H_t}{\partial \gamma_t} + (1 + r_t) \cdot \frac{\partial K_t}{\partial \gamma_t}\end{aligned}$$

This equation provides a relation between the partial derivatives of capital to climate-related damages:

$$\frac{\partial K_t}{\partial \gamma_t} = \frac{\frac{(2-\alpha\rho)\cdot Y_t}{H_t \cdot (1-\rho)} - R_t}{(1 + r_t)} \cdot \frac{\partial H_t}{\partial \gamma_t}$$

It remains to be verified that:

$$\frac{\partial}{\partial \gamma_t} ln\left(\frac{K_t}{H_t}\right) \leq 0 \Leftrightarrow \frac{1}{H_t} \cdot \frac{\partial H_t}{\partial \gamma_t} \geq \frac{1}{K_t} \cdot \frac{\partial K_t}{\partial \gamma_t}$$

There are two cases:

1. $\partial H_t / \partial \gamma_t \leq 0$. The relation between the partial derivatives of capital to climate-related damages gives:

   $$R_t H_t + (1 + r_t) K_t \leq \frac{(2 - \alpha\rho) Y_t}{(1 - \rho)}$$

   Recall that:

   $$\alpha Y_t = R_t H_t + (1 + r_t) K_t$$

   Then, rewriting gives:

   $$\alpha \leq 2$$

   which is always satisfied. Therefore,

   Lemma 7. *The elasticity of tangible capital to climate-related damages is higher than the*

elasticity of intangible capital, i.e.

$$\frac{1}{K_t} \cdot \left| \frac{\partial K_t}{\partial \gamma_t} \right| \geq \frac{1}{H_t} \cdot \left| \frac{\partial H_t}{\partial \gamma_t} \right|$$

Consequently, wage inequality increases in climate-related damages if $\partial H_t / \partial \gamma_t \leq 0$.

2. $\partial H_t / \partial \gamma_t \geq 0$. Lemma A1 ensures that:

Corollary 6. *The partial derivatives of H_t, K_t and Y_t to γ_t have the same sign, i.e.*

$$\frac{\partial H_t}{\partial \gamma_t} \geq 0 \implies \frac{\partial K_t}{\partial \gamma_t} \geq 0 \implies \frac{\partial Y_t}{\partial \gamma_t} \geq 0$$

Then, $\partial H_t / \partial \gamma_t \geq 0 \implies \partial Y_t / \partial \gamma_t \geq 0$. This is a contradiction, since $\mathcal{F}_\gamma \leq 0$. Therefore, Case 2 is ruled out and wage inequality increases in climate-related damages.

2.10.8 Proof of Proposition 8

The return to tangible capital is given by

$$(1 + r_t^*) = A^\rho \alpha (1 - \eta) \frac{\tilde{Y}_t^{1-\rho}}{\left((1 - \mu_K \gamma_t) K_t \right)^{1-\alpha\rho}} l_t^{(1-\alpha)\rho}$$

Using logarithmic differentiation, the derivative of r_t^* to γ_t becomes

$$\frac{\partial r_t^*}{\partial \gamma_t} = \frac{(1-\rho)}{Y_t} \cdot \frac{\partial Y_t^{net}}{\partial \gamma_t} - (1 - \alpha\rho) \left[\frac{1}{K_t} \cdot \frac{\partial K_t}{\partial \gamma_t} - \frac{\mu_K}{(1 - \mu_K \gamma_{t+1})} \right]$$

For $\rho = 0$, this derivative becomes

$$\left. \frac{\partial r_t^*}{\partial \gamma_t} \right|_{\rho=0} = \frac{1}{Y_t^{net}} \cdot \frac{\partial Y_t}{\partial \gamma_t} - \frac{1}{K_t} \cdot \frac{\partial K_t}{\partial \gamma_t} + \frac{\mu_K}{(1 - \mu_K \gamma_{t+1})}$$

Recall that

$$\begin{aligned}\frac{\partial}{\partial \gamma_t}\tilde{Y}_t &= \frac{\partial \tilde{Y}_t}{\partial H_t}\cdot\frac{\partial H_t}{\partial \gamma_t} + \frac{\partial \tilde{Y}_t}{\partial K_t}\cdot\frac{\partial K_t}{\partial \gamma_t} \\ &= R_t \cdot \frac{\partial H_t}{\partial \gamma_t} + (1+r_t)\cdot\frac{\partial K_t}{\partial \gamma_t}\end{aligned}$$

and that

$$\left.\frac{\partial K_t}{\partial \gamma_t}\right|_{\rho=0} = \frac{\frac{2\cdot\tilde{Y}_t}{H_t} - R_t}{(1+r_t)}\cdot\frac{\partial H_t}{\partial \gamma_t} \Leftrightarrow \left.\frac{\partial H_t}{\partial \gamma_t}\right|_{\rho=0} = (1+r_t)\cdot\frac{\partial K_t}{\partial \gamma_t}\cdot\frac{H_t}{2\tilde{Y}_t - R_t H_t}$$

then

$$\begin{aligned}\left.\frac{\partial r_t^*}{\partial \gamma_t}\right|_{\rho=0} &= \frac{\partial K_t}{\partial \gamma_t}\cdot\left[(1+r_t)\cdot\left(\frac{2}{2\tilde{Y}_t - R_t H_t}\right) - \frac{1}{K_t}\right] + \frac{\mu_K}{(1-\mu_K\gamma_{t+1})} \\ &= \frac{\partial K_t}{\partial \gamma_t}\cdot\frac{2}{K_t\cdot(2\tilde{Y}_t - R_t H_t)}\cdot\left((1+r_t)K_t + R_t H_t - \tilde{Y}_t - 1/2 R_t H_t\right) + \frac{\mu_K}{(1-\mu_K\gamma_{t+1})}\end{aligned}$$

Recall that

$$\alpha\tilde{Y}_t = R_t H_t + (1+r_t)K_t$$

Then

$$\left.\frac{\partial r_t^*}{\partial \gamma_t}\right|_{\rho=0} = \underbrace{\frac{\partial K_t}{\partial \gamma_t}}_{\leq 0}\cdot\underbrace{\frac{2}{K_t\cdot(2\tilde{Y}_t - R_t H_t)}}_{\geq 0}\cdot\underbrace{\left((\alpha-1)\tilde{Y}_t - 1/2 R_t H_t\right)}_{\leq 0} + \underbrace{\frac{\mu_K}{(1-\mu_K\gamma_{t+1})}}_{\geq 0} \geq 0$$

Note that $\frac{\partial r_t^*}{\partial \gamma_t}$ falls in ρ:

$$\begin{aligned}\frac{\partial r_t^*/\partial\gamma_t}{\partial \rho} &= -\frac{1}{Y_t}\cdot\frac{\partial Y_t}{\partial \gamma_t} + \frac{\alpha}{K_t}\cdot\frac{\partial K_t}{\partial \gamma_t} - \frac{\alpha\mu_K}{(1-\mu_K\gamma_t)} \\ &= \frac{\partial K_t}{\partial \gamma_t}\cdot\left[\frac{\alpha}{K_t} - \frac{2(1+r_t)}{2Y_t - R_t H_t}\right] - \frac{\alpha\mu_K}{(1-\mu_K\gamma_t)} \\ &= \underbrace{\frac{\partial K_t}{\partial \gamma_t}}_{\leq 0}\cdot\underbrace{\left[\frac{2}{K_t(2Y_t - R_t H_t)}\right]}_{\geq 0}\cdot\underbrace{[\alpha Y_t - (1+r_t)K_t - \alpha R_t H_t + \alpha/2\cdot R_t H_t)]}_{\geq 0} - \underbrace{\frac{\alpha\mu_K}{(1-\mu_K\gamma_t)}}_{\geq 0} \leq 0\end{aligned}$$

Nevertheless, for $\rho = 1$, the derivative remains positive, i.e.

$$\left.\frac{\partial r_t^*}{\partial \gamma_t}\right|_{\rho=1} = (1-\alpha)\left[-\frac{1}{K_t} \cdot \underbrace{\frac{\partial K_t}{\partial \gamma_t}}_{\leq 0} + \underbrace{\frac{\mu_K}{(1-\mu_K \gamma_{t+1})}}_{\geq 0} \right] \geq 0$$

Since $\rho \in [0,1)$, it holds that the cost of capital *rises* is climate-related damages.

2.10.9 Proof of Proposition 9

Share prices are given by

$$e_t^* = \frac{(1-\omega) R_{t+1} H_{t+1}}{1 + r_{t+1}}$$

i.e.

$$e_t^* = (1-\omega) \cdot \frac{\eta}{(1-\eta)} \cdot \left(\frac{\tilde{h}}{\tilde{l}}\right)^{(1-\alpha)\rho} \cdot H_{t+1}^{\alpha\rho} \cdot \left(\left(1-\mu_K \gamma_{t+1}\right) K_{t+1}\right)^{(1-\alpha\rho)}$$

Using logarithmic differentiation, the derivative of e_t^* to γ_{t+1} becomes

$$\frac{\partial e_t^*}{\partial \gamma_{t+1}} = \frac{\alpha\rho}{H_{t+1}} \cdot \frac{\partial H_{t+1}}{\partial \gamma_{t+1}} + (1-\alpha\rho)\left[\frac{1}{K_{t+1}} \cdot \frac{\partial K_{t+1}}{\partial \gamma_{t+1}} - \frac{\mu_K}{(1-\mu_K \gamma_{t+1})}\right]$$

For $\rho = 0$, this derivative becomes

$$\left.\frac{\partial e_t^*}{\partial \gamma_{t+1}}\right|_{\rho=0} = \frac{1}{K_{t+1}} \cdot \underbrace{\frac{\partial K_{t+1}}{\partial \gamma_{t+1}}}_{\leq 0} - \underbrace{\frac{\mu_K}{(1-\mu_K \gamma_{t+1})}}_{\geq 0} \leq 0$$

Note that $\frac{\partial e_t^*}{\partial \gamma_{t+1}}$ increases in ρ, as

$$\frac{\partial e_t^* / \partial \gamma_{t+1}}{\partial \rho} = \alpha \left[\frac{\mu_K}{(1-\mu_K \gamma_{t+1})} + \frac{1}{H_{t+1}} \cdot \frac{\partial H_{t+1}}{\partial \gamma_{t+1}} - \frac{1}{K_{t+1}} \cdot \frac{\partial K_{t+1}}{\partial \gamma_{t+1}}\right]$$

Following Proof of Proposition 5, this derivative is positive and increases monotonically in climate risk.

Since the derivative remains negative for $\rho = 1$, i.e.

$$\left.\frac{\partial e_t^*}{\partial \gamma_{t+1}}\right|_{\rho=1} = \frac{\alpha}{H_{t+1}} \cdot \underbrace{\frac{\partial H_{t+1}}{\partial \gamma_{t+1}}}_{\leq 0} + (1-\alpha)\left[\frac{1}{K_{t+1}} \cdot \underbrace{\frac{\partial K_{t+1}}{\partial \gamma_{t+1}}}_{\leq 0} - \underbrace{\frac{\mu_K}{(1-\mu_K \gamma_{t+1})}}_{\geq 0}\right] \leq 0$$

and $\rho \in [0, 1)$, it holds that share prices *decline* is climate risk.

2.11 General Equilibrium with Firms

I introduce a general equilibrium framework that incorporates firms. Firms operate for a single period and produce the non-durable consumption good, using physical and intangible capital, alongside labour supplied by households. A flood occurs in each period and damages the firms' physical capital, hindering its production.[52] Besides endogenizing wages, the interest rate, and the production of the non-durable consumption good, the purpose of introducing firms is to study the effects of climate risk on relative prices and credit allocation.

2.11.1 Households

The characterization of household preferences is equivalent to the one provided in the simple model (see Section III.A.1). Floods destroy the housing capital of households (following Section III.B) and households adapt to climate change (following Section V.A). In the general equilibrium framework, wages are endogenous and are equal to the marginal productivity of the respective labour type. Skill levels remain exogenously given. However, the general equilibrium framework features a third type of household, high-skilled workers who have some entrepreneurial talent.

[52] Adaptation by firms is covered in a model extension, in Appendix C.6

Innovators

A fraction $\varepsilon \in (0,1)$ of high-skilled workers has some entrepreneurial talent. These 'innovators' create intangible capital when they are young (Döttling and Perotti, 2017). Intangible capital lacks any physical presence and rather represents information (cf. Corrado, Hulten, and Sichel, 2009; Corrado and Hulten, 2010; Crouzet, Eberly, Eisfeldt, and Papanikolaou, 2022a). Intangibles can thus be regarded as knowledge capital and are created through investments like research and development or human capital and skill accumulation (Crouzet et al., 2022a). The investment is given by $I_{H,t}$, where $I_{H,t} = H_{t+1}$, and requires an effort cost:

$$C\left(I_{H,t}\right) = \frac{1}{2} I_{H,t}^2$$

I assume that intangible capital is non-rival in use (Crouzet et al., 2022a; Crouzet, Eberly, Eisfeldt, and Papanikolaou, 2022b). That is, innovators invest in intangible capital once, and may deploy the intangible capital within multiple firms.

2.11.2 Firms

There is a unit mass of firms in the economy, which operate a single period and maximize profits.

Production Technology

Firm produce the non-durable consumption good, using physical capital and intangible capital in the production process. Physical capital (K) is complementary to low-skilled labour (l; see e.g., Krusell, Ohanian, Ríos-Rull, and Violante (2000), Goldin and Katz (2009), Eisfeldt, Falato, and Xiaolan (2023)), while intangible capital (H) is complementary to high-skilled labour (h). Output, Y_t, is produced according to the following

constant elasticity of substitution production technology:

$$\begin{aligned} Y_t &= A\mathcal{F}(H_t, h_t, K_t, l_t) \\ &= A\left[\eta\left(H_t^{\alpha} h_t^{1-\alpha}\right)^{\rho} + (1-\eta)\left(K_t^{\alpha} l_t^{1-\alpha}\right)^{\rho}\right]^{\frac{1}{\rho}} \end{aligned}$$

with A a technology parameter, $\rho \in [0, 1)$ the substitution parameter, and η a distribution parameter reflecting the relative productivity of intangible capital and high-skilled labour.[53]

Capital Investments

While intangible capital is created through the effort of innovators, physical capital is created upon (monetary) investment, with $I_{f,K,t} = K_{f,t+1}$. Tangible, as well as intangible capital, depreciate fully after the production period (i.e. $\delta_K = \delta_H = 1$). Firms operating in $t = 0$ are endowed with an initial stock of physical capital, K_0, and the old innovators at $t = 0$ are endowed with an initial stock of intangible capital, H_0.

Appropriation of Intangibles

The value of intangible capital may be captured and privately appropriated (Crouzet et al., 2022a,b). Specifically, innovators can hold up the firm, by threatening to withdraw their human capital (Hart and Moore, 1994). This hinders the firm's production and enables the innovators to appropriate part of the value generated by its intangible capital (Eisfeldt and Papanikolaou, 2014; Eisfeldt et al., 2023). Let $\omega \in (0, 1]$ represent the innovator's bargaining power over the returns generated by intangible capital (Döttling and Perotti, 2017). Accordingly, innovator capture a fraction ω of the value of intangible capital, while the firm's shareholders receives the remaining fraction.

[53] To ensure that wages of high-skilled workers are higher than those of low-skilled workers, I assume that high-skilled labour is relatively scarce (see Döttling and Perotti, 2017), i.e.,

$$\frac{\phi}{1-\phi} \leq \frac{\eta}{1-\eta}$$

Climate Risk and Firm Capital

Firms are exposed to climate change, as floods destroy its physical capital (Bilal and Känzig, 2024; Acharya, Johnson, Sundaresan, and Tomunen, 2022).[54] Let $\gamma_{t+1} \in [0,1]$ capture the probability that a given firm experiences losses due to flooding in period, $t+1$. This probability is common among firms and, by the law of large numbers, corresponds to the fraction of firms that experience climate-related damages in any period $t+1$. Denote by $\xi_{f,t+1} \in [0,1]$ the losses of a given firm, f, in period, $t+1$. These losses follow some distribution, $G\left(\xi_{f,t}\right)$, which is i.i.d. across firms. The losses are idiosyncratic, reflecting that flooding events may hit certain firms harder than others. However, as idiosyncratic risk can be diversified, it is the expected losses that matter to investors. Denote by $\mu_K \in [0,1]$ the expected losses, as a fraction of physical capital, conditional on experiencing losses due to flooding. The expected idiosyncratic losses are given by:

$$\begin{aligned}\mathbb{E}\left(\xi_{f,t+1}\right) &= \mathbb{E}\left(\xi_{f,t+1}\middle|\text{Hit by the flood}\right)\cdot\mathbb{P}\left(\text{Hit by the flood}\right)\\ &= \mu_K\gamma_{t+1}\end{aligned}$$

Climate-damages reduce the amount of physical capital which has productive value:

$$\tilde{K}_t = \left(1-\xi_{f,t}\right)K_t$$

Climate-related damages thus hinder production[55]:

[54] While intangible capital, which may represent system-wide infrastructure can also be affected by physical climate risk, I take physically localized view and abstract from damages to intangible capital. This is in accordance with Acharya et al. (2022), who show that tangible industries (e.g., construction, mining, oil & gas, utilities, manufacturing and forestry & fishery) are more exposed to physical climate risk than service industries.

[55] In the environmental economics literature climate-related damages to production are modeled using a damage function (see e.g., Golosov et al., 2014; Nordhaus, 1992). Specifically, a damage function, which rises in temperatures, reduces TFP. While I model climate-related damages to production as a physical capital loss of fraction $\xi_{f,t}$, the production function can be rewritten as

$$\tilde{Y}_t = A\left[\eta\left(H_t^{\alpha}h_t^{1-\alpha}\right)^{\rho} + (1-\eta)\left(1-\xi_{f,t}\right)^{\alpha\rho}\left(K_t^{\alpha}l_t^{1-\alpha}\right)^{\rho}\right]^{\frac{1}{\rho}}$$

$$\tilde{Y}_t = A\mathcal{F}(H_t, h_t, \tilde{K}_t, l_t), \qquad \mathcal{F}'_\gamma(H_t, h_t, \tilde{K}_t, l_t) \leq 0$$

and reduce the firm's output. In contrast to damages to the housing stock, climate-related damages to the physical capital stock affect a firm's output only within the given period, as the firms' capital stock depreciates fully after each production period. Consequently, climate-related damages affect firms on a *flow* basis. In contrast, in the housing market, the supply of habitable houses experiences a permanent decline over time, indicating that climate-related damages have a *stock* effect.

2.11.3 Firm Financing and Financial Markets

Each firm, f, issues corporate debt to finance the investment in physical capital. Corporate debt, which has a face value of $D_{f,t}$, is funded by households with positive savings. The corporate debt held by household i in firm f in period t is denoted by $D_{i,f,t}$ and the total holdings of corporate debt of a given household are denoted by $D_{i,t} = \int_0^1 D_{i,f,t} df$. Lending to firms occurs against collateral, and the firm's physical capital backs its corporate debt. Corporate debt earns a risk-free rate of return, r_t, and is repaid each period.[56]

Innovators also issues equity, which is backed by the value of the share of intangible capital appropriated by equity holders. I denote the equity held by shareholder i in firm f in period t by $s_{i,f,t}$ and the total equity holdings of a given household are denoted by $s_{i,t} = \int_0^1 s_{i,f,t} df$. I normalize the quantity of shares of each firm to 1. The price of a share of firm f is denoted by $e_{f,t}$, and shares receive a dividend payment, $d_{f,t}$, at the end of the period.

This function reflects that climate-related damages reduce firm's overall productivity of physical inputs (i.e. low-skilled labour and physical capital). This specification also captures a decline in the productivity of manual labour due to, e.g., heat-stress (Acharya et al., 2022).

[56] While physical capital is also exposed to climate-related risks, I abstract from corporate default in the model. This simplify the analysis and maintains the focus on the allocation of resources and the economic consequences of climate risks, while avoiding the complexities of modeling default.

2.11.4 General Equilibrium

Household Optimization Problem

Households maximize utility subject to the budget constraint and limited liability constraint:

$$\begin{aligned}\max_{c_{i,t+1},L_{i,t},s_{i,t},S_{i,t},x_{i,t}} \mathbb{E}\left(U(c_{i,t+1},L_{i,t})\right) &= \mathbb{E}_t\left(c_{i,t+1}\right)+v\left(L_{i,t}\right)\\ s.t.\quad y_{i,t} &\leq \left(p_t+\frac{1}{2}x_{i,t}^2\right)L_{i,t}+s_{i,t}e_t+S_{i,t}\\ c_{i,t+1} &\leq \max\{y_{i,t+1}+p_{t+1}(1-\xi_{i,t+1})L_{i,t}+d_{t+1}s_{i,t}+(1+\hat{r}_{t+1})S_{i,t},0\}\\ c_{i,t+1},L_{i,t},x_{i,t} &\geq 0,\end{aligned}$$

where $\mathbb{E}_t$ denotes expectations formed at date t.

Within the general equilibrium framework, the optimal demand for housing and adaptation matches that of the simple framework, as outlined in Section V.B.2. In the general equilibrium framework, the risk-free rate is time-variant.
The share price follows from households' demand for share holdings, $s_{i,t}$ and is equal to the discounted value of the dividend payment, d_{t+1}

$$e_t = \frac{d_{t+1}}{(1+r_{t+1})}$$

Investments in corporate and household debt follow as residual. Households with net savings lend to others households and firms, while households with negative savings take out a mortgage.

Firm Optimization problem

Firms maximize the value to its equity holders. Since firms only operate for one period, and pay out all profits, the maximization problem is given by:

$$\max_{H_t,h_t,K_t,l_t} \pi_{f,t} = \tilde{Y}_t(A, H_t, h_t, \tilde{K}_t), l_t) - \omega R_t H_t - q_t h_t - (1 + r_t) D_{t-1} - w_t l_t$$

Labour markets are perfectly competitive, which implies that high-skilled and low-skilled workers earn their marginal productivity.

Lemma 8. *Wages of high- and low-skilled workers, q_t respectively w_t are equal to*

$$q_t^* = A^\rho (1-\alpha)\eta \cdot \frac{\tilde{Y}_t^{1-\rho}}{h_t^{1-(1-\alpha)\rho}} \cdot H_t^{\alpha\rho}$$
$$w_t^* = A^\rho (1-\alpha)(1-\eta) \cdot \frac{\tilde{Y}_t^{1-\rho}}{l_t^{1-(1-\alpha)\rho}} (1-\mu_K \gamma_t)^{\alpha\rho} \cdot K_t^{\alpha\rho}$$

The wage ratio is defined as $\frac{q_t^*}{w_t^*}$ and is given by:

$$\frac{q_t^*}{w_t^*} = \frac{\eta}{1-\eta} \cdot \left(\frac{H_t}{(1-\mu_K \gamma_t) K_t}\right)^{\alpha\rho} \cdot \left(\frac{l_t}{h_t}\right)^{1-(1-\alpha)\rho}$$

Climate-related damages lead to a decline in income, reducing wages of high- and low-skilled workers. However, the damages to physical capital have a direct, negative impact on the productivity of low-skilled workers. As a result, the skill premium rises, leading to a rise in wage inequality. The skill premium also depends on the balance of intangible and physical capital used in production. Firms (and innovators) scale back their investments as income declines. However, as tangible capital is more vulnerable to climate risks, firms scale back their investments in physical capital to a greater extent. This further reduces the productivity of low-skilled workers relative to high-skilled workers over time.[57]

[57] This result also holds if intangible capital were exposed to climate risk, as long as the elasticity of tangible capital to climate-related damages is larger than the elasticity of intangible capital to climate-related damages.

Proposition 7. Wage inequality rises in climate-related damages.

Proof: See Appendix A.7

Firms are financially unconstrained and borrow up to the point where the marginal cost of capital is equal to its marginal productivity

Lemma 9. *The return to physical capital is given by*

$$(1 + r_t^*) = A^{\rho}\alpha(1-\eta) \cdot \frac{\tilde{Y}_t^{1-\rho}}{\left((1-\mu_K\gamma_t)\,K_t\right)^{1-\alpha\rho}} \cdot l_t^{(1-\alpha)\rho}$$

and firms fully finance the investment in physical capital by debt in each period, $I_{K,t}^* = D_t$.

The return on physical capital determines the cost of capital and is affect by climate change along two channels.[58] First, climate-related damages reduce the firm's income, $\tilde{Y}$. In response, firms cut back their investments, reducing capital demand and lowering the return on physical capital. However, and second, the return to physical capital also depends directly on the amount of physical capital, K, used in production. Since physical capital is vulnerable to climate risks, physical capital becomes riskier and, in response, firms scale back their investments in physical capital to a greater extent - thus reducing the firms' relative reliance on physical capital. In equilibrium, the risk-channel dominates, and the cost of capital rise in climate-related damages.

Proposition 8. The cost of capital rises in climate-related damages.

Proof: See Appendix A.8

The rise in the cost of capital has redistributive implications. Specifically, as the cost of capital rises, households with positive savings accumulate wealth at a faster rate. In contrast, households that finance the purchase of housing capital by issuing household debt face an increase in the costs of servicing their mortgage contract. Hence, through the costs of capital channel, savings act as an *unequalizing* force, increasing wealth inequality.

[58] Redistributive technological change (reflected by a rise in η) produces a decline in interest rates due to excess savings (Döttling and Perotti, 2017). Excess savings arise as technological change increases the reliance of the economy on intangible capital, reducing demand for physical capital and corporate debt.

Shareholders capture a fraction $(1-\omega)$ of the return to intangibles capital. In equilibrium, dividends are given by:

$$\begin{aligned} d_t^* &= \tilde{Y}_t(H_t, \tilde{K}_t, h_t, l_t) - (\omega R_t^* H_t + q_t^* h_t + (1 + r_t^*)K_{t-1} + w_t^* l_t) \\ &= (1-\omega)R_t^* \cdot H_t \end{aligned}$$

where the return on intangible capital is given by[59]

$$R_t^* = A^\rho \alpha \eta \cdot \frac{\tilde{Y}_t^{1-\rho}}{H_t^{1-\alpha\rho}} \cdot h_t^{(1-\alpha)\rho}$$

Share prices are given by the discounted value of the dividend payment:

$$e_t^* = \frac{(1-\omega)R_{t+1} \cdot H_{t+1}}{1 + r_{t+1}}$$

Lemma 10. *Climate-related damages reduce dividends.*

Since climate-related damages hinder the firm's production, the firm experiences a decline in its output and therefore its profitability. This reduces the dividend payment *(cashflow effect)*. Simultaneous, the cost of capital rises *(discount rate effect)*. Through both channels, firm's equity prices are suppressed.

Proposition 9. Share prices decline in climate risk.

Proof: See Appendix A.9

The decline in equity prices reduces the financial wealth of shareholders. Therefore, financial asset price changes act as an *equalizing* force for the wealth distribution.[60]

[59] Competitive firms pay a return on intangible capital equal to its marginal productivity. Given the return, innovators create an amount of intangible capital equal to:

$$I_t^* = \frac{\omega}{\phi\varepsilon} R_{t+1}^* = \tilde{\omega} R_{t+1}^*$$

where $I_t^* = H_{t+1}^*$ (Döttling and Perotti, 2017).

[60] Bauluz, Novokmet, and Schularick (2022) study the rise of global saving and wealth between 1980-2018. One of the authors' finding is that saving were an unequalizing force for the wealth distribution, while capital gains were an equalizing force.

Equilibrium and Market Clearing

A competitive equilibrium is defined as an allocation $\{c_t^l, c_t^h, L_t^l, L_t^h, s_t^l, s_t^h, D_t^l, D_t^h, K_t, H_t, l_t, h_t\}_{t=0}^T$ and prices $\{p_t, e_t, r_t, R_t, w_t, h_t\}_{t=0}^T$ such that in each period, t, given prices

1. Households maximize lifetime utility;

2. Firms maximize profits;

3. Innovators optimally choose intangible investment;

and all markets clear.

Within the general equilibrium framework, the housing market clearing condition and the expression for the price of housing capital, p_t, are similar to those of the simple framework, as outlined in Sections V.C. In the general equilibrium framework, the risk-free rate becomes time-variant.

Total labour demand equals total labour supply, so that

$$\int_0^1 \left[h_{f,t}^d, l_{f,t}^d\right] df = [h^s, l^s]$$

Households supply their entire labour endowment since the marginal product of labour is strictly positive. Therefore, $[h^s, l^s] = \{\phi\bar{h}, (1-\phi)\bar{l}\}$ and the labour market equilibrium requires:

$$\int_0^1 \left[h_{f,t}^d, l_{f,t}^d\right] df = \{\phi\bar{h}, (1-\phi)\bar{l}\}$$

Aggregate income of young households must equal the value of assets that carry savings over time. This consists of the aggregate investment in housing, corporate debt and shares:

$$(1-\alpha)\tilde{Y}_t - p_t\bar{L}_t = e_t + D_t$$

where $(1-\alpha)\tilde{Y}_t = q_t\phi\bar{h} + w_t(1-\phi)\bar{l}$. For equity markets to clear, the total share holdings must equal the total supply of shares:

$$\int_0^1 s^*_{i,t} di = 1$$

Recall that the investment in physical capital is fully financed by corporate debt, i.e. $D_t = K_t$. Hence, the financial market clearing condition provides an expression for the supply of physical capital:

$$K_t = (1-\alpha)\tilde{Y}_t - p_t\bar{L}_t - e_t$$

2.11.5 Endogenous Supply of Adaptation Capital

Households invest in adaptation by channeling part of their resources to adaptation capital. Thus far, the supply of adaptation capital was considered exogenous. The supply can be endogenized by requiring households to sacrifice part of their labour endowment. Specifically, households must use some of their time to take preventive measures that protect their housing capital. Denote the amount of high-skilled respectively low-skilled labour that a household must sacrifice, for a given choice of adaptation $x_{i,t}$ and housing consumption $L_{i,t}$, by h_x respectively l_x, where

$$l_x, h_x = f(x_{i,t}, L_{i,t}), \quad f'_x > 0, f''_{xx} > 0, \quad f'_L > 0, f''_{LL} = 0$$

When adaptation is labour-based, the income of high- respectively low-skilled households is given by:

$$y_l = w \cdot (\tilde{l} - l_x) \qquad y_h = q \cdot (\tilde{h} - h_x)$$

For simplicity, assume that

$$l_x = \frac{1}{2} \cdot \frac{x_l^2 L_l}{w} \qquad h_x = \frac{1}{2} \cdot \frac{x_h^2 L_h}{q}$$

Labour-based adaptation reduces the income of households by an amount equal to what they would have spent on adaptation in monetary terms. Hence, the private choice of adaptation is equivalent to the solution derived in Section V.B.2. However, less labour can be used in production, this strengthens the negative effect of climate change on output, the more so if climate risk rises.

2.11.6 Adaptation by Firms

The general equilibrium framework abstracted from adaptation by firms. In this extension, I study the effect of adaptation by firms on output and the costs of capital.[61] Suppose firms invest in climate change adaptation at the same time they invest in physical capital. Denote by $x_{f,t} \in [0,1)$ the choice of adaptation of firm f in period t. This investment comes at a cost. Specifically, the investment costs are given by $\psi(x_{f,t}, K_{f,t}) = \frac{1}{2} K_{f,t}(x_{f,t})^2$. Similarly as to the household-setting, the costs increase linearly in the amount of physical capital protected, and the investment costs rise at an accelerating rate in the choice of adaptation.

By adapting to climate change, firms reduce protect themselves against climate-related damages in the next period. Specifically, for a given choice of adaptation, $x_{f,t}$, the firm prevents a fraction $x_{f,t}$, of the idiosyncratic losses. Hence, adaptation leads to a leftward shift in the distribution of losses by $x_{f,t} \cdot \mu_K \gamma_{t+1}$. In expectation, the losses experienced by a given firm, $\xi_{f,t+1}$, are:

$$\mathbb{E}\left(\xi_{f,t+1}\right) = \left(1 - x_{f,t}\right) \mu_K \gamma_{t+1}$$

By reducing damages to physical capital used in production, adaptation reduces the

[61] Acharya, Bhardwaj, and Tomunen (2023) document that firms in the United States respond to heat stress by reducing employment in the affected locations and increasing it in unaffected locations, preventing heat-related decline in labour productivity. Balboni et al. (2023) find that flood-affected firms in Pakistan are more likely to relocate to safer areas, and shift purchases towards suppliers in less flood-prone regions. Bilal and Rossi-Hansberg (2023) model adaptation through migration and capital investment decisions in a spatial macroeconomic model, finding that anticipation of future climate damages amplifies climate-induced worker and investment mobility.

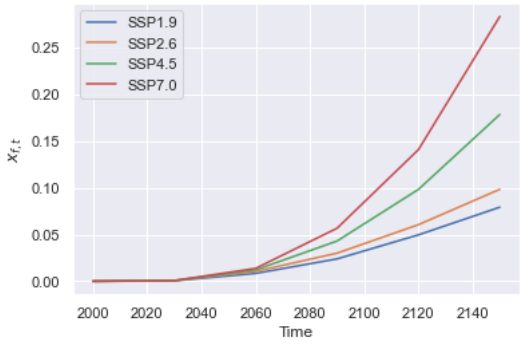


Figure 2.11.6: The evolution of the firm's choice of adaptation, $x_{f,t}$, under the SSP1-1.9, SSP1-2.6, SSP2-4.5 and SSP3-7.0 scenario.

decline in output:

$$Y_{t+1} = A\left[\eta\left(H_{t+1}^{\alpha}h_{t+1}^{(1-\alpha)}\right)^{\rho} + (1-\eta)\left(\left[\left(1-(1-x_{f,t})\mu_K\gamma_{t+1}\right)K_{t+1}\right]^{\alpha}l_{t+1}^{(1-\alpha)}\right)^{\rho}\right]^{\frac{1}{\rho}}$$

I assume that firms can pledge the adaptation capital as collateral. Then, firms borrow to finance the investment in adaptation capital.

Lemma 11. *The optimal choice of adaptation by firms is implicitly defined as:*

$$x_{f,t}^{*} = A^{\rho}\alpha(1-\eta)\cdot\frac{\tilde{Y}_{t+1}^{1-\rho}}{\left((1-(1-x_f)\mu_K\gamma_{t+1})K_{t+1}\right)^{1-\alpha\rho}}\cdot l_{t+1}^{(1-\alpha)\rho}\cdot\frac{\mu_K\gamma_{t+1}}{(1+r_{t+1})}$$

Figure 2.11.6 plots the evolution of the firm's choice of adaptation over time, showing that the firm's choice of adaptation rises as climate change worsens. Under the most severe climate change scenario, firms invest to reduce more than 25 percent of idiosyncratic losses by the end of the century. This reduces the fall in output. Adaptation by firms is neutral on the cost of capital. By adapting to climate change, firms reduce the decline in aggregate income. This increases the supply of capital in the economy compared to the case in which firms do not adapt, thus reducing the cost of capital. However, firms finance their investment in adaptation by issuing corporate debt. This raises demand for capital, thus increasing the cost of capital. In equilibrium, these two effects fully offset one another.

Chapter 3

The Political Economy of Climate Change Adaptation[1]

Abstract

We study the evolution of voter support for climate policy when preferences respond to rising climate risk and economic inequality. Households differ in age, income and beliefs, and vote on public intervention to protect households from climate shocks. Support for preventive policy is initially low, gradually rising as climate risk increases. Beliefs on climate risk converge over time, while beliefs on public effectiveness persist and lead to rising disagreement. The political choice of climate intervention jumps at a tipping point driven by rising climate damage, as long as political beliefs are not too far apart. Rising inequality may induce a second tipping point. Agents do not fully internalize the effect of loss of habitat, leading to higher house prices. The political conflict combines with the *"tragedy of the horizon"* to produce underinvestment under any coalition.

Keywords: Climate change adaptation, economic inequality, tragedy of the horizon, political tipping points.

JEL codes: D63, H23, Q54, Q58.

[1] This chapter is based on Van der Straten, Perotti & Van der Ploeg (2024). The Political Economy of Climate Change Adaptation. CEPR Discussion Paper DP18959.

3.1 Introduction

Climate change leads to a gradual rise in global temperatures, destabilizing the weather system. Extreme weather events, such as severe storms, rising sea levels and desertification reduce habitatable land and the housing stock, and undermine living conditions. Following a period of rising awareness in recent years which led to a phase of public intervention, preferences have shifted markedly, leading to a policy stall on climate risk mitigation efforts as policy responses – which are often time-inconsistent – tend to face political backlash once their costs become visible Besley and Persson, 2023; Hsiao, 2023.

As the green transition picks up slowly, global warming is likely to continue in the coming decades. As sea levels rise and extreme weather events intensify in the near future, climate shocks grow larger, accelerating the loss of habitable land (Burzyński, Deuster, Docquier, and De Melo, 2019). Individuals and corporations will adapt to a changing climate, either through self-protective measures (e.g., Fried, 2022; Van der Straten, 2023) or by reallocating capital via financial markets (Kahn, Ouazad, and Yönder, 2024). Yet most climate damage is best contained by large-scale investments in public adaptation to limit the impact of global warming. Such a collective effort is fiscally costly, and depends on political support.

We study a context in which global warming and climate risk are expected to persist, and examine how political support for public damage control evolves over time. Our analysis takes place against a backdrop of rising economic inequality – an important driver of increasingly polarized views (Voorheis, McCarty, and Shor 2015), especially with regard to climate policy preferences (Douenne and Fabre, 2022). Climate shocks damage the housing stock and lead to degradation of habitable land (e.g., through rising sea levels, desertification or ecological degradation Van der Straten (2023)). The economic impact is considerable: housing accounts for two-thirds of global wealth, and a tenth of the housing stock is already under climate threat.[2] Physical damage from extreme climate event or gradual climate change may be contained by protective

[2] See, e.g., "Homeowners face a $25trn bill from climate change" in The Economist, (April 11, 2024).

infrastructure, so underinvestment leads to more loss of housing and habitat. On the other hand, public intervention requires support for its fiscal cost.

We consider a political environment in which households differ by age, income, and beliefs – three key predictors of voter support for climate policies (Dechezleprêtre, Fabre, Kruse, Planterose, Chico, and Stantcheva, 2022).[3]

We study how majority coalitions around climate policy evolve over time in an overlapping generation context where climate risk and inequality steadily rise.[4] Households derive utility from consumption and their own housing. They also partially internalise habitat conditions for their children in the near future.[5] In each period, households vote for the coalition favoring the adaptation rate closest to their preference. In the basic model households vote before they know their future income (thus under a Rawlsian veil of ignorance), though they are aware of rising inequality.

There are two possible notions of diverging beliefs. We first consider different priors on actual climate risk, a debate most evident over several decades (see e.g., Murfin and Spiegel, 2020; Baldauf, Garlappi, and Yannelis, 2020; Bakkensen and Barrage, 2021). Learning from the experience of climate events should, in principle, resolve political conflict over time. For such conflict to persist, there must be some fundamental difference in opinion or ideology among voters. We therefore consider political beliefs over public policy effectiveness.[6] While the updating of climate change beliefs lead to convergence in preferences over time, with rising agreement on public policy, voter preference do not converge under political beliefs.

Our aim is to better understand how political coalitions respond over time to a rising climate threat. We focus on the realistic case in which the old cohort is more numerous

[3] Dechezleprêtre et al. (2022) explore international attitudes toward climate policies. Their results indicate that support for an active climate policy is influenced by its perceived effectiveness in reducing emissions, redistributive effects on lower-income households, and direct impact on people's own households.

[4] Our model builds on the redistributive growth framework outlined in Döttling and Perotti (2017) to capture the effect of long term trends.

[5] This implies caring for 'the world we leave for our children', as opposed to caring for the long term climate on the planet.

[6] Survey evidence suggests that skepticism often centers not on the existence of global warming, but on the perceived effectiveness of climate measures (Douenne and Fabre, 2022).

or politically active than the young cohort, and skeptic voters constitute a majority in any age or income cohort. Feasible political majorities can be formed by a coalition of the older cohort leading to low public investment, a more proactive coalition of old and young skeptics moderately supportive of an active policy, or a most proactive coalition of young skeptics and old realists.

We show that when political beliefs are more polarized, age differences matters less. Thus young skeptics emerge as the pivotal group in the political equilibrium. Initially as climate risk is limited the skeptic young have a weaker motive to support public intervention. Consequently, the initial majority coalition consists of skeptics households of all ages who favour limited public policy. Less preventive policy leads to a faster loss of houses and habitat and increases house values. As climate risk rises, more support for public adaptation emerges among all groups of voters.[7] However, the change in support varies across subgroups and their coalitions. We show that rising climate risk induces a political equilibrium tipping point, as the policy preferences of the pivotal group (young skeptics) shifts faster than for their initial allies. Young households receive a larger benefit from adaptation; as climate risk rises, residual habitat gains value, encouraging more preventive measures. As a result their preferred adaptation rate gradually moves closer to the preferences of old optimists, as shown in Figure 3.1.1. Provided that polarization is not too extreme, the winning coalition shifts once climate damages and habitat loss become sufficiently large. The political equilibrium shift leads to a jump in public adaptation. This first result is intuitive: as climate risk and inequality rise, even political coalitions dominated by skeptics and older cohorts gradually support more climate adaptation.

The more active policy still falls short of the socially optimal value, however. We refer to this difference as the *adaptation gap*. The gap is in part due to skepticism about policy efficacy that persists even when beliefs on climate risk have converged. The "tragedy of the horizon" effect adds another cause for underinvestment, as households

[7] Cain, Gerber, and Hui (2020) and Demski, Capstick, Pidgeon, Sposato, and Spence (2017) show how flood experiences reduce polarization on climate priorities and increase support for adaptation; see also Rasmussen, Kopp, Shwom, and Oppenheimer (2021); MacInnis and Krosnick (2020).

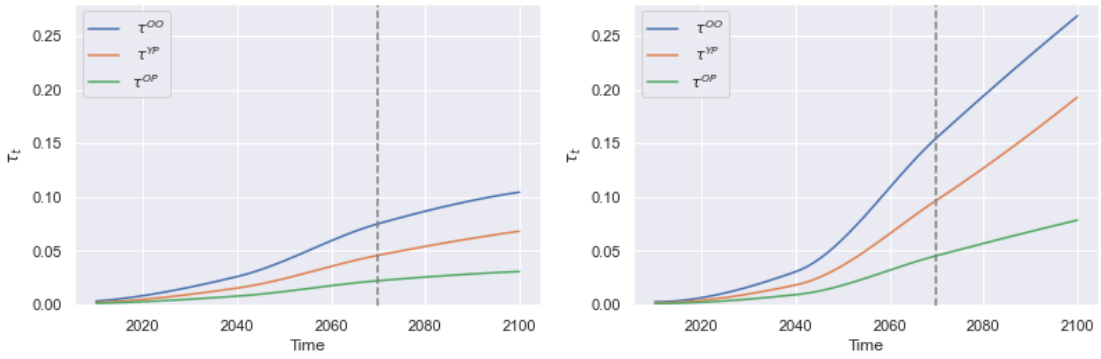


Figure 3.1.1: **Evolution of the political equilibrium**

Key: The time paths of the adaptation rate preferred by the old optimists (blue line), the young skeptics (orange line) and the old skeptics (green line) for different SSP$x-y$ scenarios. The dashed, vertical line indicates the point in time at wish the political equilibrium tips. The left panel shows the evolution of the bounds under the SSP1-2.6 scenario, in line with the aggregate Nationally Determined Contribution emission levels by 2030; the right panel shows the evolution of the bounds under the SSP3-7.0 scenario, a medium to high climate change scenario.

care more about the present and near future habitat, and do not fully internalize benefits for future generations.

We subsequently study how economic status affects voting. Household get to know their income level over time, sharpening their preferences. A steady rise in inequality leads to more favor for adaptation among low-income old workers. Over time, this induces a second political tipping point, where low-income voters join the majority coalition. Their effect on public adaptation is ambiguous. When inequality rises gradually the shift leads to less public investment in adaptation, due to the inclusion of low-income, skeptic households in the majority coalition. This produces a backlash effect, where increasing vulnerability is met with reduced collective action. When inequality rises rapidly, its impact becomes dominant; in this case, the second tipping point triggers an increase in support for public adaptation. These results reflect that the evolution of economic inequality is critical to understand the evolution of climate policy.

The remainder of paper is structured as follows. We discuss the related literature in Section 2. In Section 3 we introduce the baseline framework. The conditions relevant for the definition of an equilibrium are derived in Section 4. In Section 5, we introduce the political economy framework and derive the political equilibrium. Section 6 provides

a quantitative assessment of the evolution of the equilibrium over time. We derive the optimal policy in Section 7. We extend the model to allow for inequality in Section 8. Section 9 concludes.

3.2 Related Literature

The normative literature on climate policy studies mitigation policies such as optimal carbon pricing (e.g., Nordhaus, 2008; Golosov, Hassler, Krusell, and Tsyvinski, 2014; Dietz and Stern, 2015). Our paper relates to work on adaptation to climate change (e.g., Lasage, Veldkamp, De Moel, Van, Phi, Vellinga, and Aerts, 2014; Muis, Güneralp, Jongman, Aerts, and Ward, 2015; Fried, 2022; Van der Straten, 2023), predominantly focused on private incentives to adapt to climate change. Fried (2022) studies investments in seawalls, stilts and other choices to cope with severe storms in the US. Fried (2022) studies damages from storms, showing how idiosyncratic climate risk impacts adaptation and the welfare cost of climate change. Van der Straten (2023) studies how financial incentives shape private efforts to contain climate damage. While house values in frictionless markets fully price the effect of climate adaptation, Van der Straten (2023) shows that credit-constrained households cannot fully adapt, increasing the rate of habitat loss. The present paper focuses on the evolution of political support for tax funded adaptation aimed at protecting habitat.

Our paper relates to Hong, Wang, and Yang (2023), who analyze how the private and public sectors should adapt to manage disaster risks to the capital stock when they learn about the adverse consequences of global warming for disaster arrivals. Following Hong et al. (2023), who highlight that adaptation is more valuable under learning, political support for public adaptation rises in our framework as climate change becomes evident through the increasing frequency of extreme weather events.

Next to learning, we allow for differences in subjective perceptions on the severity of climate risks. As such, our results are related to recent studies on how learning about climate risk affect coastal housing markets (e.g., Murfin and Spiegel, 2020, Bal-

dauf et al., 2020, Bakkensen and Barrage, 2021). Bakkensen and Barrage (2021) show that heterogeneity in beliefs reconciles the mixed evidence on whether flood risk is capitalized in house prices. They find significant under-estimation of flood risks and sorting based on flood risk beliefs and amenity values.[8]

Differences in climate change perceptions also affect the response of households to climate risks in housing markets.[9] Bakkensen, Phan, and Wong (2022) show that households who are pessimistic about climate risks take up higher and longer-term mortgages. Anticipating high risk of collateral damage, households value the option to default. Bernstein, Billings, Gustafson, and Lewis (2022) show that beliefs about climate risk contribute to partisan sorting in housing markets. Voters with skeptics views on climate risk are less likely to change their sorting behavior in response to climate change - which indicates that these households may ultimately bear the burden of climate change. Our paper illustrates that these households further frustrate the political process. Therefore, skeptic voters may not only bear a larger burden themselves, but also increase the burden of climate change borne by society at large.

Our work also relates more broadly to the literature studying political economy considerations in a climate change context. Besley and Persson (2023) study the evolution of environmental values along with technology, showing a dynamic complementarity of technology and values that may either promote a green transition or create a vicious circle, leading to a so called "climate trap". Delfgaauw and Swank (2024) also develop a political-economy model of a climate trap. Our analysis differs from theirs as our focus reflects on the interplay between rising climate risk and income differences, a well documented trend Acemoglu and Autor (2011). This calls for a dynamic political economy approach, distinguishing the (perceived) impact of climate change across polarized cohorts. Intuitively, more extreme weather events or sea rise raises support for adaptation, but may increase divergence across age and income cohorts. While the

[8] In a related study, Ikefuji, Laeven, Magnus, and Yue (2022) use a hedonic pricing model to study how subjective perception of earthquake risks in five Japanese cities affect real estate prices in the short and long run.

[9] Zappalà (2024) shows that technology adoption levels are lower when farmers underestimate climate change.

literature studying political economy considerations in a climate change context has abstracted from how such differential impacts affect the political outcome, our work highlights how the tension between inequality and beliefs significantly affects the political feasibility of climate policy.

Finally, as our approach is to solve for the political majority equilibrium by considering all possible coalitions of subgroups (old versus young, high and low income, optimists versus pessimists), our work is closely related to the early political economy literature on migration and pensions (see e.g., Razin and Sadka, 1999, 2000; Razin, Sadka, and Swagel, 2002; Razin, 2021), which adopted a OLG framework to study political shifts in response to long term trends, adding climate risk to the classic focus on inequality.

3.3 Baseline Model

Time is discrete and is denoted by $t \in \{0, 1, ..., \infty\}$. The economy is characterized by two overlapping generations, where each new generation is infinitesimally smaller compared to the existing population. Thus the old generation dominates in terms of number of voters.[10] Households earn heterogeneous income in both periods and use it for consumption of housing habitat and a numeraire good in abundant supply. Climate risk rises deterministically over time. At the start of each period, an extreme weather event hits a fraction of households and damages their housing capital, reducing habitat. Households differ in their initial perception on the severity of climate risks and learn over time. We later explore the possibility that households have persistent political beliefs on the merit of public intervention. The government can reduce climate risk exposure by investing in public adaptation (e.g., building of seawalls, dykes, or stilts; funding fire departments) financed by a flat-tax on labour income. Politicians propose an adaptation rate and compete for votes in each period's electoral competition. Households vote for the politician proposing the adaptation rate closest to their

[10] This assumption reflects life expectancy and demographics in many countries. The young generation size N^Y while is lower than the old generation's N^O, where $N^Y = \varepsilon N^O$ with ε close to, but not equal to 1.

preferred amount.

3.3.1 Households

Households live for two periods and derive utility from consuming housing, and a non-durable consumption good. They also derive utility from the state of the environment inherited by the next generation. When young, households purchase housing capital, denoted by L, from the old generation at a price p. Once old, households channel the proceeds from selling the house, as well as the return earned on their savings to the purchase of a numeraire good, denoted by c. There is an initial generation at $t = 0$ endowed with the supply of houses, $\bar{L}_0$.

Preferences

Households have convex preferences over housing and linear in consumption. We adopt the notion of intergenerational altruism (Barro, 1974), departing from personal bequest (dynastic) motives. In particular, we assume households care about the collective quality of the habitat left behind, rather than individual wealth transfers.[11] Specifically, utility is increasing in the aggregate housing stock available in the next period, $\bar{L}_{t+1}$, which reflects the availability of livable land for future generations.[12] Expected lifetime utility is given by:

$$U\left(L_{i,t}, c_{i,t+1}, X_t\right) = v\left(L_{i,t}\right) + c_{i,t+1} + f\left(\bar{L}_{t+1}\right), \tag{3.3.1}$$

where $v\left(L_{j,t}\right)$ is the utility derived from housing consumption in period t, with $v'(\cdot) > 0$ and $v''(\cdot) < 0$. $f\left(L_{i,t+1}\right)$ captures the utility of leaving behind habitable land to the

[11] Housing serves both as a consumption good and as a legacy asset, reflecting an intergenerational motive. While the size of habitat determines the intergenerational wealth transfers, habitable land can be degraded due to climate risks. Public adaptation reduce climate risk exposure, preserving habitat.

[12] This specification captures a collective action problem, as each household individually undervalues the long-term benefits of adaptation. This is because the gains from preserving land accrue to all future generations, and are therefore collectively shared, while households only internalize the effect on the next generation. This incomplete internalization gives rise to a "tragedy of the horizon" effect (Carney, 2015), in which myopic preferences and the public good nature of adaptation lead to underinvestment in protective measures that have distant benefits.

next generation, with $f'(\cdot) > 0$ and $f'(\cdot) < 0$.

Income

Households earn income in each period. A fraction $\phi \leq 0.5$ of households is of the high-income type, denoted by h, and the remaining fraction $1 - \phi$ is of the low-income type, denoted by l. High-income households earn $y_{h,t} = q$, and low-income households earn $y_{l,t} = w$, where $q > w$.

3.3.2 Climate Change

The economy is exposed to rising climate risk. The common probability of an extreme weather event affecting any household in period t is denoted by γ_t, which increases deterministically over time (cf. Van der Straten, 2023). By the law of large numbers, γ_t is the fraction of households whose house suffers climate-related damages in period t. Damages, denoted by $\xi_{i,t}$, are i.i.d. shocks distributed according to $F(\xi_{i,t})$. We denote by μ the common fraction of losses to housing capital caused by an extreme weather event. We then have

$$\mathbb{E}_t(\xi_{i,t+1}) = \underbrace{\mathbb{E}_t\left(\xi_{i,t+1} \middle| \text{Hit by Extreme weather event}\right)}_{\mu} \cdot \underbrace{\mathbb{P}(\text{Hit by Extreme weather event})}_{\gamma_{t+1}}. \tag{3.3.2}$$

The housing capital of household i after an extreme weather event is reduced to

$$L_{i,t+1} = (1 - \xi_{t+1}) L_{j,t}. \tag{3.3.3}$$

Physical climate events not only destroy part of the housing stock, but also permanently degrade its land.[13] Denote the supply of livable land (cf. Burzyński et al. (2019)) in a given period by $\bar{L}_t$. Consistent with the macroeconomic literature analyzing land and

[13] Land degradation occurs over a quarter of the Earth's ice-free land area and climate change accelerates the rate and scale of ongoing land degradation processes and generates new degradation patterns IPCC (2019).

long-run economic - and house price growth, we assume that the supply of livable is fixed in the long run.[14] As a result of land degradation, the supply of habitable land therefore evolves dynamically over time and follows the law of motion:

$$\bar{L}_{t+1} = \int_0^1 (1 - \xi_{i,t+1})\, di L_t \tag{3.3.4}$$

$$\overset{\text{LLN}}{=} (1 - \mu\gamma_{t+1})\, \bar{L}_t. \tag{3.3.5}$$

Beliefs about Climate Change

The empirical literature demonstrates that climate change beliefs influence the extent to which climate risk is priced in housing markets, sorting patterns, as well as the adaptive response to extreme weather events.[15] To capture the role of climate change beliefs in shaping housing market outcomes and adaptive responses, we assume that households differ in their perceptions of the likelihood of extreme weather events. Beliefs are orthogonal to income and reflect differences in risk perception or ideology. A fraction $\omega > 0$ of households consists of skeptics (s), who underestimate climate risk, while the remaining households are realists (r), who correctly perceive the probability of climate-related disasters. In the initial state of the economy, skeptics form the majority.
Let $\theta_{j,t}$ denote the belief of a household of type $j \in \{s, r\}$ at time t about the probability that an extreme weather event occurs. Realists assign the correct probability, $\theta_{r,t} = \bar{\theta} = 1$, in every period. Skeptics instead perceive the probability as $\theta_{s,t} = \underline{\theta} < 1$, and act as

[14] See for example Ricardo (1817), who shows that economic growth benefits landlords disproportionatly due to the fixed nature of land. Nichols (1970) includes land as fixed production factor in a Solow model to show that house prices grow at the same rate as output in the steady state. Also Hansen and Prescott (2002) build a one-good, two-sector overlapping generations (OLG) model land is in fixed supply. More recently, Grossmann, Larin, and Steger (2025) consider a two-good, two-sector infinitely-lived agent model in which the land development sector becomes inactive in the long run. Combined with differences in the intensity by which land is used in different sectors, the fixed nature of land explains the rise in real house prices in the long run as observed in the data. Finally, Saiz (2010) shows empirically that the fraction of undevelopable land is higher in areas where there are regulatory or geographical constraints. This is particularly true for coastal cities, such as Miami, San Francisco, and New Orleans.

[15] Murfin and Spiegel (2020); Baldauf et al. (2020); Bakkensen and Barrage (2021) show that climate change beliefs influences the pricing of physical climate risk in housing markets. Bernstein, Gustafson, and Lewis (2019) shows that households "vote with their feet", with climate change deniers (believers) sorting in to neighborhoods which are (not) exposed to climate risks. Zappalà (2024) show that technology adoption levels are lower when farmers underestimate climate changes.

if an extreme event occurs with probability $\underline{\theta} \cdot \gamma$, where γ is the objective probability of the event. Skeptics' beliefs influences their expectation on the damages suffered due to an extreme weather event and therefore their preferences for adaptation. Specifically, the housing capital that remains in expectation after the extreme weather event for a skeptic household is given by

$$\mathbb{E}_{s,t}\left(L_{s,t+1}\right) = \left(1 - \underline{\theta} \cdot \mu\gamma_{t+1}\right) L_{s,t}. \tag{3.3.6}$$

While beliefs are initially fixed within a generation, they evolve across generations as climate impacts occur. This captures the idea that each cohort enters the economy with its own beliefs—shaped by experience and social context, and updates these in response to observed climate impacts. Following the standard learning models (cf. Hong et al., 2023), we allow for gradual belief revision between generations. Belief updating is triggered by the occurrence of extreme weather events. If such an event occurs in period t, a skeptic household adjusts its belief upwards for period $t+1$:

Definition 1. When an extreme weather event occurs in period t, a type-j household updates its belief in period $t+1$ according to:

$$\theta_{s,t+1} = \min\left\{\theta_{s,t} + \delta,\ 1\right\} \tag{3.3.7}$$

where $\delta > 0$ is a parameter capturing the responsiveness of belief updating. If no extreme event occurs, beliefs remain unchanged: $\theta_{s,t+1} = \theta_{s,t}$.

This reflects the idea that households learn from the experience of extreme weather events, but only do so gradually. While beliefs may shift toward realism over time, ideological differences persist for various generations.[16]

[16] While Hong et al. (2023) show that learning improves the adaptive response of the economy and mitigates welfare losses, other studies highlight that belief updating can be ideologically polarized. For instance, Djourelova, Durante, Motte, and Patacchini (2023) find that exposure to disasters increases climate concern among liberals but reduces it among conservatives, thereby widening the ideological divide.

3.3.3 Public Policy Intervention

Government intervention is called for to prevent a sharp fall in supply of habitat and to alleviate any underinvestment in private protection (cf. Van der Straten, 2023). There are various measures available for government intervention, such as public adaptation (e.g., the Deltawork in the Netherlands after the flood of 1953), subsidizing private adaptation, and bailing out households in case of large adverse shocks.[17] We focus on preventive measures and model public intervention as investments in public adaptation, which directly offers protection to all households in the economy.

Public Adaptation

To protect households from idiosyncratic losses when an extreme weather event occurs, the government invests in public adaptation (e.g., building of seawalls or dykes). Since large-scale adaptation investments can take substantial time to realize, this is an intertemporal investment and the pay-off is only realized in the next period. Define $X_t \in [0, 1)$ as the public choice of protection or public adaptation. It represents the percentage by which households' idiosyncratic losses from climate shocks are prevented in period $t + 1$.

For a given choice of public adaptation, the distribution of household losses $F(\xi_{i,t+1})$ is shifted to the left:

$$\mathbb{E}_t\left(\xi_{i,t+1}\right) = \left(1 - X_t\right)\mu\gamma_{t+1}. \tag{3.3.8}$$

Hence, public intervention reduces the losses of all households.[18] For each household, the expectation of the housing capital that remains preserved after the extreme weather

[17] The first two policy measures are *preventive*. The third measure is a form of *corrective* action. Corrective action may not always be effective, however, as bailouts may trigger moral hazard. Another form of corrective action is the restoration of habitat. This may be more difficult than preventing its loss ex ante. We therefore assume that this is prohibitively costly.

[18] Note that adaptation does not increase the utility from consuming housing in the current period. Rather, adaptation increases household utility by raising the stock of undamaged housing capital which can be sold in the next period.

event is then

$$L_{i,t+1} = (1 - (1 - X_t)\,\mu\gamma_{t+1})\,L_{j,t}. \tag{3.3.9}$$

Since adaptation preserves housing capital and habitable land, it reduces the speed at which its supply shrinks. Then, the supply of houses evolves according to the following law of motion:

$$\bar{L}_{t+1} = \int_0^1 (1 - \xi_{i,t+1})\,di \cdot \bar{L}_t \tag{3.3.10}$$

$$\overset{\text{LLN}}{=} (1 - (1 - X_t)\,\mu\gamma_{t+1})\,\bar{L}_t. \tag{3.3.11}$$

Finance of Public Adaptation

Investments in public adaptation come at a cost, $\psi(X_t) = \frac{1}{2}\bar{L}_t X_t^2$. These costs are proportional to the aggregate housing stock, $\bar{L}$, since larger areas require more extensive and resource-intensive infrastructure.[19] The investment costs rise at an accelerating rate in the choice of adaptation, indicating that even the most ambitious investments cannot entirely prevent climate-related losses and damages (Van der Straten, 2023).

We assume that public adaptation is financed with a flat labour income tax, τ_t, which we refer to as the adaptation rate. The tax burden is shared among young and old households, and taxes cannot be targeted at a social group.[20] The budget constraint for household i in each period t is

$$(1 - \tau_t)\,y \leq p_t L_{i,t} + S_{i,t}. \tag{3.3.12}$$

[19] For example, protecting a larger area involves constructing longer and potentially taller dykes, which increases the quantity of materials needed. This directly raises costs in proportion to the protected land area. Also, expanding the coverage of a dyke system involves addressing more varied geographical features, such as rivers, coastal regions, and floodplains. This brings forward engineering complexities, which scale with the size of the protected region.

[20] If neither spending nor taxes can be targeted to specific voter groups and politicians cannot appropriate tax revenues, policy preferences will become monotonic with respect to income. Specifically, as taxes are proportional to income, richer households will tend to prefer a smaller government, while poorer households will tend to favor a larger government (cf. Persson and Tabellini, 2002).

Political Process

In each period, households vote over the level of public adaptation. Adaptation investments reduce expected climate-related damages in the following period. The electorate includes both young and old households, and the policy is implemented by an elected government. We assume a simple voting process: two politicians compete in a majoritarian election by proposing specific adaptation rates, and households cast their votes for one of the two politicians. The adaptation rate supported by the majority is implemented.

Because households live for two periods, both young and old generations participate in voting and contribute to financing public adaptation. While both generations pay taxes, they benefit from adaptation in different ways. Young households benefit directly through reduced damages to their housing, which increases its future resale value. Old households benefit indirectly through their bequest motive, which becomes more relevant the stronger their altruistic preferences for the next generation.

A key determinant of voting preferences is belief heterogeneity. Households differ in their perception of climate risk, which directly affects how much households value adaptation. Let $X^*_{i,j,t}$ denote the individually preferred level of public adaptation by household $i \in \{Y, O\}$, with belief type $j \in \{r, s\}$ at time t. Each household votes for the policy closest to $X^*_{i,j,t}$, and the equilibrium policy X^*_t is determined by the majority preference. Over time, the beliefs of skeptics evolve endogenously, moving closer to those of realists as they update their perceptions based on observed climate impacts. This gradually shifts the majority coalition's policy support over time.

3.3.4 Housing Market Dynamics

The housing market opens after the extreme weather events takes place. Since destroyed housing capital has zero liquidation value, households with a mortgage risk default and pay the risky rate of return, $\hat{r} \geq r$, where the interest rate r is exogenous.

Net savings of a household i in period t is defined as

$$S_{i,t} \equiv y_{i,t} - p_t L_{j,t}, \tag{3.3.13}$$

where $S_{i,t} \geq 0$ indicates that household i is a net lender and $S_{i,t} < 0$ implies it is a net borrower. Default occurs once losses become sufficiently large, i.e.,

$$p_{t+1} L_{i,t+1} \leq (1 + \hat{r})(-S_{i,t}). \tag{3.3.14}$$

The loan-to-value ratio is defined by

$$LTV_{i,t+1} \equiv \frac{(1 + \hat{r})(-S_{i,t})}{p_{t+1} L_{j,t}}. \tag{3.3.15}$$

This implicitly defines the threshold of losses above which a homeowner defaults by

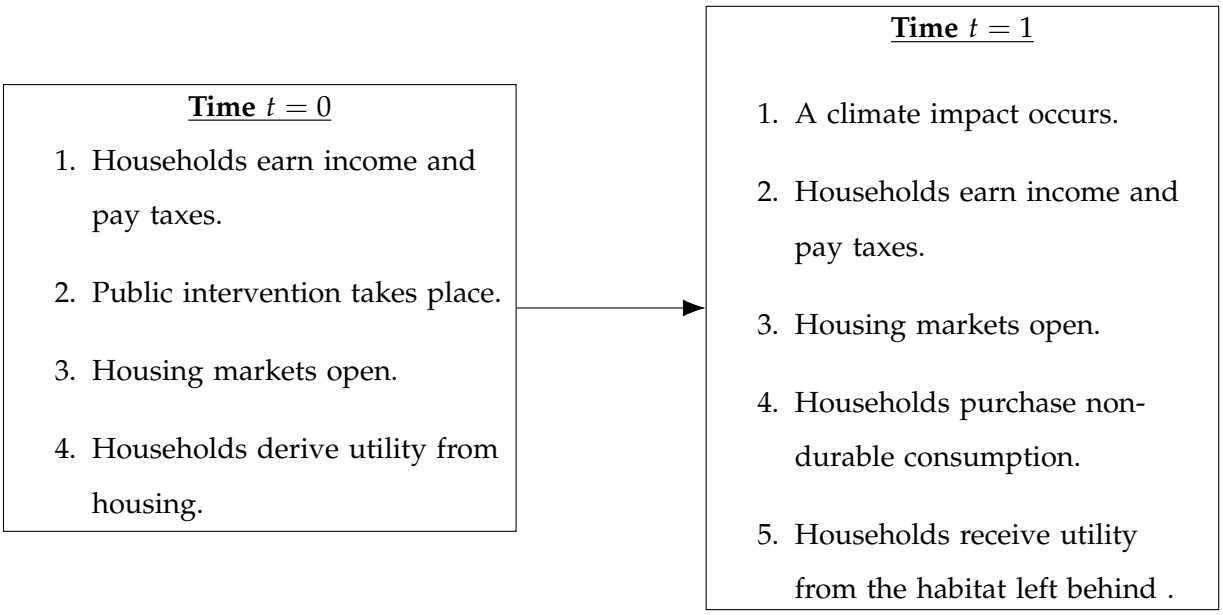
$$\hat{\bar{\xi}}_{i,t+1} = 1 - LTV_{i,t+1}, \tag{3.3.16}$$

while the probability of default is

$$\chi_{i,t} = \left(1 - F\left(\hat{\bar{\xi}}_{i,t+1}\right)\right). \tag{3.3.17}$$

3.3.5 Timing of Events

The timeline of each individual household in the baseline model is illustrated below:



where the household is young in period $t = 0$, and old in period $t = 1$.

3.4 Equilibrium

Households maximize expected utility subject to their budget constraints, credit constraint and a limited liability constraint:

$$\max_{L_{i,j,t}, S_{i,j,t}, c_{i,j,t+1}} \mathbb{E}\left(U\left(L_{i,j,t}, c_{i,j,t+1}, X_t\right)\right) = v\left(L_{i,j,t}\right) + \mathbb{E}_{i,j,t}\left(c_{i,j,t+1}\right) + \mathbb{E}_{i,j,t}\left(f\left(\bar{L}_{t+1}\right)\right) \tag{3.4.18}$$

$$\begin{aligned} s.t. \quad & (1-\tau_t)\, y_{i,t} \leq p_t \cdot L_{i,j,t} + S_{i,j,t} \\ & c_{i,j,t+1} \leq (1-\tau_{t+1})\, y_i + \max\left\{ p_{t+1}\left(1-\xi_{i,t+1}\right) L_{i,j,t} + \left(1+\hat{r}\right) S_{i,j,t}, 0 \right\} \\ & L_{i,j,t}, c_{i,j,t+1} \geq 0, \end{aligned}$$

where $c_{i,jt+1}$ denotes the consumption of household i, j in period $t+1$.

3.4.1 Demand for Housing Capital

Due to the quasi-linearity of preferences, housing demand is independent of a households' income. Households' perception on the severity of climate risk does affect housing demand, however. Since skeptics expect a larger fraction of their housing capital to

remain undamaged after the climate impact - and therefore to have a positive liquidation value - they have a higher demand for housing.

Lemma 1. *Demand for housing in period t equals*

$$L^*_{j,t} = L^*_{i,t} = v'^{-1}\left((1+r)p_t - \left(1-\mu\left(1-X_t\right)\cdot\theta_{j,t}\cdot\gamma_{t+1}\right)\cdot p_{t+1}\right). \tag{3.4.19}$$

This implicitly defines the price of housing capital in period t, which equals

$$p_t = \frac{\left(1-\mu\left(1-X_t\right)\cdot\theta_{j,t}\cdot\gamma_{t+1}\right)\cdot p_{t+1} + v'(L^*_t)}{(1+r)}. \tag{3.4.20}$$

Demand for housing determines house price . The price today reflects the discounted value of the total benefits from owning housing. These include the utility households derive from consuming housing in the current period, captured by $v'\left(L^*_t\right)$, and the expected revenue from selling undamaged housing capital at the start of the next period. Specifically, the expected benefit from the next period equals the future price p_{t+1}, which is discounted for the expected fraction of housing that becomes damaged, which depends on the beliefs of the marginal buyer θ_j, the objective risk exposure γ_{t+1}, and the level of public adaptation X_t.

3.4.2 Demand for Household Debt

Household debt follows residually. Households with net savings lend to others households while households with negative savings take out a mortgage.

3.4.3 Equilibrium and Market Clearing

A competitive equilibrium is an allocation $\{c_{t+1}, L_t, S_t\}_{t=0}^T$ and prices $\{p_t, \tau_t\}_{t=0}^T$, so that in each period, t, given prices, households maximize lifetime utility and all markets clear.

Housing market

Total housing demand equals total housing supply, so that

$$\int_0^{\omega} L_{s,t}^* ds + \int_{\omega}^1 L_{r,t}^* dr = \bar{L}_t. \tag{3.4.21}$$

Using Lemma 1, a housing market equilibrium requires

$$\bar{L}_t = \left(1 - \left(1 - X_{t-1}\right) \mu \gamma_t\right) \bar{L}_{t-1}. \tag{3.4.22}$$

Financial market

Aggregate after-tax income of young households must in equilibrium equal aggregate investment in housing. Hence,

$$\left(1 - \tau_t\right) \cdot \int_0^1 y_{i,t}^Y di = p_t\left(\theta_j, X_t\right) \bar{L}_t, \tag{3.4.23}$$

where aggregate gross labour income of the young is

$$\int_0^1 y_{i,t}^Y di = \phi q + \left(1 - \phi\right) w. \tag{3.4.24}$$

Government budget balance

Government tax revenues must equal the convex costs of public adaptation,

$$\tau_t \cdot \left(\int_0^1 y_{i,t}^Y di + \int_0^1 y_{i,t}^O di\right) = \frac{1}{2} X_t^2 \bar{L}_t, \tag{3.4.25}$$

where aggregate gross income of the old is the same as that of the young.

$$\int_0^1 y_{i,t}^O di = \int_0^1 y_{i,t}^Y di = \phi q + \left(1 - \phi\right) w. \tag{3.4.26}$$

Housing Market Clearing Condition

The housing market clearing condition pins down the equilibrium price of housing capital:

$$p_t^* = \frac{\left(1 - \mu\left(1 - X_t^*\right) \int_0^1 \theta_{j,t} dj \cdot \gamma_{t+1}\right) \cdot p_{t+1} + v'(\bar{L}_t)}{1 + r}. \tag{3.4.27}$$

Over time, two dynamics shape the evolution of house prices in the presence of climate risk. First, climate damages reduce the supply of habitat. Since households are risk-averse with respect to housing consumption, the reduction in supply increases the marginal utility of housing and thereby households' willingness to pay for housing. This raises the contemporaneous price of housing – a mechanism similar to that in Van der Straten (2023).

Moreover, belief heterogeneity feeds into prices through aggregation. As households endogenously revise their beliefs about climate change, they increasingly internalize the impact of climate-related damages on the resale value of housing. The imperfect internalization of climate risk puts upwards pressure on prices by weakening the effect of the exposure of housing to future damages. Crucially, the larger the dispersion in climate risk perceptions, the more muted the risk-exposure effect (i.e., the sea-level rise discount effect; see e.g., Baldauf et al. (2020); Bernstein et al. (2019); Bakkensen and Barrage (2021)) becomes. This hinders the capitalization of climate risk and can lead to rising house prices under weaker conditions than in the rational agent case.[21]

Financial Market Clearing

If labour income is insufficient to cover the purchase of a house, some agents need to borrow. Because at least one type of workers must have positive savings (cf. Döttling

[21] We derive the equilibrium condition under which the supply effect dominates in Appendix A1. Compared to Van der Straten (2023), this condition is less restrictive because of the belief heterogeneity. As some households underestimate their true exposure to climate risk, the downward pressure on prices from perceived exposure is weakened, while the upward pressure from the supply reduction remains unchanged due to market clearing. As a result, house prices may rise with climate risk for values of relative risk aversion (RRA) below one.

and Perotti, 2017), the volume of mortgage credit in the economy, m, is

$$m_t = \max\left\{0, \int_0^{(1-\phi)} L_{i,t} di \cdot p_t - (1-\tau_t)\, w\right\}. \tag{3.4.28}$$

If households are sufficiently risk averse with respect to their housing consumption, public adaptation limits the upwards effect that climate change has on house prices. On the other hand, taxation reduces disposable income, which increases mortgage credit demand.

3.5 Political Economy

Public adaptation is the outcome of electoral competition in which young and old households vote. Specifically, two politicians compete in a majoritarian election by proposing specific public adaptation levels, and households cast their votes for one of the two politicians. Households are heterogeneous in terms of their income and their beliefs about climate change, and vote for the politician which proposes a adaptation rate closest to their preferred policy. We first consider the case in which households vote under a Rawlsian veil of ignorance, hence before income-types are revealed ($t = 0$) and before the impact of the climate shock ($t = 1$). This allows us to first isolate the effects of belief dispersion on the political equilibrium. In an extension, we consider the case in which households get to know their income-type over time as they vote.

3.5.1 Preferred Adaptation Rates

When households vote under a Rawlsian veil of ignorance, they are not yet aware of their income type. This creates four distinct groups in society, with preferences for adaptation shaped by both age and climate change beliefs. Household prefer an adaptation rate that maximizes their expected lifetime utility.

Lemma 2. *The preferred adaptation rate of a young household i with beliefs θ_j is*

$$\tau_t^{Yij*} = \frac{1}{\bar{L}_t} \cdot [\phi q + (1-\phi)\, w] \cdot \left(\frac{\tilde{\theta}_{j.t} \cdot \mu \gamma_{t+1} \cdot (p_{t+1} + \pi_{j,t})}{(1+r) y_{i,t}} \right)^2, \tag{3.5.29}$$

and the preferred adaptation rate of a old household i with beliefs θ_j is

$$\tau_t^{Oij*} = \frac{1}{\bar{L}_t} \cdot [\phi q + (1-\phi)\, w] \cdot \left(\frac{\tilde{\theta}_{j.t} \cdot \mu \gamma_{t+1} \cdot \pi_{j,t}}{y_{i,t}} \right)^2, \tag{3.5.30}$$

where we define

$$\pi_{j,t} \equiv f(\mathbb{E}_{j,t}(\cdot)) / \partial\, \mathbb{E}_{j,t}(\cdot) \tag{3.5.31}$$

and $y_{i,t} = \phi q + (1-\phi)\, w$, since households vote under a Rawlsian veil of ignorance with respect to their income type. Finally, we denote by $\tilde{\theta}_{j,t}$ the belief-weighted exposure of household type j.

Proof: See Appendix A2.B.

The preferred adaptation rate of households in both age groups increases as climate risk (γ_{t+1}) intensifies and the supply of habitable land ($\bar{L}_t$) diminishes. These factors increase the need for protective measure and, consequently, raise the support for public adaptation. Additionally, households with stronger perceptions on the severity of climate change ($\tilde{\theta}_{j.t}$) favor higher adaptation rates, as they view public adaptation as more critical in addressing rising climate risks, indicating that $\tau^{Yir*} > \tau^{Yis*}$ and $\tau^{Oir*} > \tau^{Ois*}$. Similarly, the preferred adaptation rate rises with the marginal utility of leaving behind habitat ($\partial f(\cdot)/\partial(\cdot)$), as households place greater value on the benefits of public adaptation for the welfare of the future generation. Conversely, the preferred adaptation rate decreases with individual income levels, as the tax burden is proportional to income. However, it increases with higher aggregate labor income ($\phi q + (1-\phi)\, w$), reflecting society's greater capacity to shoulder the tax burden. Finally, and distinctively, the young's preferred adaptation rate increases with the house prices (p_{t+1}), which reflects

the value of housing which is potentially lost upon a climate impact. Becomes of the intertemporal nature of the investment, adaptation reduces only the risk exposure of young households, who become the homeowners. This indicates that the old have relatively less to gain from public adaptation. Hence, the adaptation preferred by the old is less than that of the young, i.e., $\tau^{Yij*} > \tau^{Oij*}$.

3.5.2 Feasible Coalitions

To win an election, politicians must secure a majority of votes. Lemma 2 shows that households' preferred adaptation rate varies based on their age and their beliefs about climate change. Since no single group is large enough to constitute a majority, voters must form coalitions to ensure the implementation of their preferred policy. The initial set of potential coalitions include: (i) all young households, (ii) young and old realists, (iii) all old households, (iv) young and old skeptics, (v) young realists and old skeptics, and (vi) young skeptics and old realists. Our modeling assumptions identify a realistic subset of these coalitions. Specifically, coalitions (i) and (ii) are too small to form a majority and influence the political equilibrium. Moreover, Lemma 2 implies that coalition (v) is too ideologically dispersed.

We focus on majority coalitions which are both internally and externally stable. That is, no member prefers to leave and form an alternative coalition, and no party outside the coalition can join and improve outcomes for all members. We assume that coalitions choose an adaptation rate that maximizes their joint utility, subject to their budget constraints.

Lemma 3. *If there are fewer young than old households and skeptics constitute a majority ($\omega > 0.5$), then the set of feasible coalitions is either (i) a coalition of young skeptics and old realists with preferred adaptation rate,*

$$\tau_t^{Ys,Or*} = A \cdot \left(\frac{\omega \tilde{\theta}_{s,t} p_{t+1} + \left(\omega \cdot \tilde{\theta}_{s,t} + (1-\omega) \cdot \tilde{\theta}_{r,t}\right) \cdot \pi_{s,r,t}}{(1+\omega r)} \right)^2, \tag{3.5.32}$$

or (ii) a coalition of young and old skeptics with preferred adaptation rate,

$$\tau_t^{Ys,Os*} = A \cdot \left(\frac{\tilde{\theta}_{s,t} \left(\frac{1}{2} p_{t+1} + \pi_{s,t} \right)}{\left(1 + \frac{1}{2} r \right)} \right)^2, \tag{3.5.33}$$

or (iii) a coalition of the old with preferred adaptation rate,

$$\tau_t^{Or,Os*} = A \cdot \left(\left(\omega \cdot \tilde{\theta}_{s,t} + (1 - \omega) \cdot \tilde{\theta}_{r,t} \right) \cdot \pi_{r,s,t} \right)^2. \tag{3.5.34}$$

Common terms in the adaptation rates are defined by

$$A \equiv A\left(\bar{L}_t, \gamma_{t+1}\right) = \frac{\left(\mu \gamma_{t+1}\right)^2}{\bar{L}_t} \cdot \frac{1}{\left[\phi q + (1 - \phi)\, w\right]}. \tag{3.5.35}$$

Proof: See Appendix A2.B.

The adaptation rate proposed by each coalition increases with intensifying climate risk (γ_{t+1}), diminishing habitable land supply ($\bar{L}_t$), rising aggregate labor income ($\phi q + (1 - \phi) w$), higher future house prices (p_{t+1}), and in the marginal utility of leaving behind livable land ($\partial f(\cdot)/\partial(\cdot)$). These factors collectively reflect the increasing need to adapt as climate risks rise. The proposed adaptation rates also rise in the belief-weighted climate exposure ($\tilde{\theta}_{j,t}$), highlighting the role of beliefs in shaping political outcomes. Moreover, the adaptation rates proposed by a coalition of old realists and young skeptics, as well as by a coalition of old realists and skeptics, increase with the share of realists, $1 - \omega$.

The political equilibrium hinges on two key factors: (i) whether young skeptics choose to form a coalition with old skeptics or old realists, and (ii) whether old skeptics prefer to align with young skeptics or old realists.

Lemma 4. *Define by $\tilde{\Theta} \equiv \tilde{\theta}_{r,t} / \tilde{\theta}_{s,t}$ the dispersion in beliefs between skeptics and realists. If it holds that*

Assumption 1. $\tilde{\Theta} > \frac{p_{t+1} + \pi_{s,t}}{\pi_{r,t} \cdot (1+r)}$.

then, the preferred adaptation rates satisfy

$$\tau_t^{YO*} > \tau_t^{Or*} > \tau_t^{Or,Ys*} > \tau_t^{Ys*} > \tau_t^{Or,Os*} > \tau_t^{Ys,Os*} > \tau_t^{Os*}. \tag{3.5.36}$$

Under Assumption 1, old realists prefer to form a coalition with young skeptics rather than old skeptics. Conversely, if Assumption 1 does not hold, old households form the majority coalition, and the prevailing adaptation rate is:

$$\tau_t^{Or,Os*} = A \cdot \left(\left(\omega \cdot \tilde{\theta}_{s,t} + (1-\omega) \cdot \tilde{\theta}_{r,t} \right) \cdot \pi_{r,s,t} \right)^2. \tag{3.5.37}$$

The ordering of preferred adaptation rates in Lemma 4 reflects the interplay of age and climate change beliefs in shaping political dynamics. Young realists propose the highest adaptation rate, as they face the longest horizon to experience the benefits of reduced climate risks, and also have an accurate perception of climate risks. Old skeptics, by contrast, propose the lowest rate, as their short remaining time horizon reduces the perceived benefits of adaptation, and they underestimate the risks the economy is exposed to.

For old realists to prefer a higher adaptation rate than young skeptics ($\tau^{Or*} > \tau^{Ys*}$), belief dispersion must be sufficiently large. On the one hand, young skeptics gain directly from public adaptation through reduced damages to the housing they own, making them inclined to support a more involved public adaptation policy. However, they underestimate climate risks. Old realists, in contrast, have an accurate perception of climate risks. Yet, only if the dispersion in beliefs is sufficiently large, this effect will dominate. Assumption 1 provides a sufficient condition for this to hold, as under this assumption the adaptation rates satisfy $\tau_t^{Or*} > \tau_t^{Or,Ys*} > \tau_t^{Or,Os*}$. Given that utility of old realists is concave in the adaptation rate and rises for $\tau_t \leq \tau_t^{Or*}$, forming a coalition with young skeptics provides higher utility to old realists than forming a coalition with old skeptics. The strict ranking of preferences ensures that this equilibrium is unique, and both internally and externally stable. As climate risk intensifies over time, Assumption 1 becomes increasingly harder to satisfy, as rising climate risk leads to

habitat loss, which in turn drives up house prices. This raises the economic stakes for young skeptics, who benefit from public adaptation as it reduces expected damages to their increasingly valuable housing capital.

3.5.3 Political Tipping

The young skeptics are the pivotal group in shaping political outcomes under Assumption 1, with their preferences influencing coalition formation and thereby the public adaptation policy chosen. The equilibrium thus hinges on whether young skeptics prefer to form a coalition with old realists or old skeptics.

Proposition 1. *Let there be less young than old, skeptics then represent a majority ($\omega > 0.5$), Assumption 1 is satisfied and $v(L_{j,t}) = ln(L_{j,t})$. Then, if*

$$\tilde{\Theta} < \left(\frac{1}{\pi_{r,s,t}} \left(\frac{1+\omega r}{(1-\omega)} \cdot \sqrt{\left(\frac{B}{\tilde{\theta}^2_{s,t}} + \frac{1}{\left(1+\frac{1}{2}r\right)^2} \cdot \left(\frac{1}{2} p_{t+1} + \pi \right)^2 \right)} - p_{t+1} \right) - 1 \right) \tag{3.5.38}$$

the political economy equilibrium is then characterized by a coalition of young skeptics and old realists. The adaptation rate proposed by this coalition equals

$$\tau_t^{Ys,Or*} = A \cdot \left(\frac{\omega \cdot \tilde{\theta}_{s,t} \cdot p_{t+1} + \pi_{r,s,t} \cdot \left(\omega \cdot \tilde{\theta}_{s,t} + (1-\omega) \cdot \tilde{\theta}_{r,t} \right)}{(1+\omega \cdot r)} \right)^2 . \tag{3.5.39}$$

If condition (3.5.38) on the dispersion of beliefs is not satisfied, the political economy equilibrium is characterized by a coalition of young and old skeptics with adaptation rate

$$\tau_t^{Ys,Os*} = A \cdot \left(\frac{\tilde{\theta}_{s,t} \left(\frac{1}{2} p_{t+1} + \pi_{s,t} \right)}{\left(1+\frac{1}{2}r\right)} \right)^2 . \tag{3.5.40}$$

Proof: See Appendix A1.B.

Proposition 1 highlights that at low levels of climate risk, young skeptics prefer to form a coalition with old skeptics. This is driven by their shared perceptions about the severity of climate change, creating ideological alignment, even as economic incentives

between young and old differ. However, as climate risk intensifies, the economic incentives of these groups diverge. Habitat loss resulting from climate change increases house prices, which raises the preferred adaptation rate of young relative to that of old. While rising climate risk raises the preference for public adaptation across all households, the preferred rate of young rises more rapidly. This is because the economic value of public adaptation in protecting housing assets increases. Hence, public adaptation becomes more significant for young skeptics over time.

If beliefs are not too dispersed, the political equilibrium evolves over time. While initially dominated by a coalition of all young and old skeptics, the equilibrium may shift toward a coalition of young skeptics and old realists. The increasing alignment between these groups in response to rising climate risk may bring forward "political tipping". The coalition of young skeptics and old realists supports a higher adaptation rate, therefore bringing forward a discrete jump in the intensity of public adaptation policies. This reflects young skeptics' growing interest in addressing their rising economic stakes from climate change.

The young skeptics emerge as the pivotal group only when beliefs about climate change are sufficiently dispersed (as outlined in Assumption 1). However, for political tipping to occur — and thus to shift to a more intensive public adaptation policy — beliefs must not be too dispersed. When belief dispersion is moderate, young skeptics' economic interests align with the ideological interests of the old realists, making a coalition with them increasingly relevant. Conversely, if beliefs are too polarized, the ideological gap between skeptics and realists outweighs the increased economic value of adaptation for the young skeptics. In that case, the young skeptics continue to prefer a coalition with the old skeptics, despite their increasingly divergent economic interests.

3.5.4 Fundamental Differences of Opinions

While habitat loss brings forward the possibility of political tipping, the occurrence of extreme weather events allows households to update their beliefs about climate risk

exposure. Therefore, the political conflict resolves as $t \to \infty$, even for low speeds of of learning (δ), given that beliefs converge over time. Yet empirically, we do not observe such convergence or a consistent increase in climate action, even as extreme weather events become more frequent and severe.

This suggests that persistent political disagreement may not be due to differences in perceived exposure to climate risk, but rather to ideological or institutional factors. To reflect this, we assume that households hold different beliefs about what should be done about rising climate risk or the effectiveness of public adaptation, rather than its necessity. Specifically, let $\vartheta_j \in \{\underline{\vartheta}; \bar{\vartheta}\}, j \in \{r, s\} \leq 1$ denote the subjective belief of a household of type j about the effectiveness of public adaptation. We continue to refer to households with $\underline{\vartheta} > 0$ as skeptics, and those with $\bar{\vartheta} > \underline{\vartheta}$ as realists. In this case, beliefs of households, ϑ_j, are independent of households' perception of their climate risk exposure. Instead, they reflect ideological views or the (perceived) quality of public institutions.[22]

Introducing belief heterogeneity in the effectiveness of adaptation preserves the core structure of the analysis: the first-order conditions for the preferred adaptation rate remain unchanged compared to the case when households had different beliefs about climate change. However, this modification alters the dynamics of the model. It allows political disagreement to persist even in the long run, since convergence in perceived climate risk does not imply convergence in political trust or institutional beliefs. As a result, the political system may remain polarized despite increasing climate impacts.

[22] For instance, Douenne and Fabre, 2022 use survey data to show that French households reject a carbon tax - and dividend policy, because these households overestimate their monetary losses after the protests of the Yellow Vests movement. Moreover, the authors show that these households do not perceive the policy as environmentally effective, and tend to discard positive information about it - which highlights their mistrust.

Parameter	Description	Value	Source
μ	Conditional expectation of losses to housing capital	1	Sea-level rise
$\bar{L}$	Housing stock	1	Normalization
ϕ	Fraction of high skilled labour	0.20	Van der Mooren and De Vries (2022)
ω	Fraction of pessimists	0.51	Initial majority
q	Wage of high-income households	0.167	Van der Straten (2023)
r	Rate of interest	0.718	Van der Straten (2023)
w	Wage of low-income households	0.089	Van der Straten (2023)

Table 3.6.1: **Parameter Values.**

3.6 Quantitative Assessment of Political Equilibrium Tipping

To illustrate the equilibrium effects of rising climate risk on the political equilibrium, we provide a parameterization based on the Dutch economy. The Netherlands is extremely prone to flooding. Specifically, 59% of land area prone to flooding (Ligtvoet and Knoop, 2014) and 48% of the houses is at risk of direct inundation (Klimaateffectatlas, n.d.). This area is densely populated, with approximately 70% of population residing here. The Netherlands also has a long history in flood risk management. Since flood risk is the main climatic impact in the Netherlands, the country offers an ideal closed-economy context for this study.

We run our model for the periods 2010 till 2100, with each time period equal to 30 years. We conduct counterfactual analysis to demonstrate the effects of different scenarios of sea level rise, based on a low greenhouse gas emission-scenario (SSP1-1.9, SSP1-2.6), an intermediate greenhouse gas emission-scenario (SSP2-4.5) and a high greenhouse gas emission-scenario (SSP3-7.0) based on IPCC (2023).[23]

[23] The SSP$x-y$ scenarios describe different climate futures depending on socio-economic trends underlying the scenario (x) and the approximate level of radiative forcing (in watts per square meter) resulting from the scenario in the year 2100 (y). Under SSP1-1.9 (SSP1-2.6), global warming remains approximately below 1.5 (2.0) degrees Celsius above 1850-1900 in the year 2100, which is the target of the Paris Agreement. This scenario requires net zero CO2 emissions by 2050 (in the second half of the century). SSP2-4.5 is in line with the aggregate Nationally Determined Contribution emission levels by 2030. Under this scenario, global warming reaches approximately 2.7 degrees Celsius above 1850-1900 by the end of the century. SSP3-7.0 is a medium to high climate change scenario. Under this scenario, global warming reaches approximately 3.6 degrees Celsius above 1850-1900 by the end of the century.

We use the illustrative parameter values stated in Table 3.6.1 (cf. Van der Straten, 2023).[24] [25] For the purpose of illustrating the effects of the model, we let γ_t represent the fraction of the currently flood-safe houses that a future rise in sea levels would put at risk of flooding) (cf. Van der Straten, 2023). We rely on Bosker, Garretsen, Marlet, and van Woerkens (2019), who provide estimates of the number of currently flood safe houses that a future rise in sea levels would put at risk of flooding of at least 50 centimeters for various levels of sea level rise.[26] To approximate the evolution of γ_t under different scenarios of sea level rise, we use the NASA Sea Level Projection Tool (Garner, Hermans, Kopp, Slangen, Edwards, Levermann, Nowicki, Palmer, Smith, Fox-Kemper, Hewitt, Xiao, Aðalgeirsdóttir, Drijfhout, Golledge, Hemer, Krinner, Mix, Notz, Nurhati, Ruiz, Sallée, Yu, Hua, Palmer, and Pearson, 2021; Fox-Kemper, Hewitt, Xiao, Aðalgeirsdóttir, Drijfhout, Edwards, Golledge, Hemer, Kopp, Krinner, Mix, Notz, Nowicki, Nurhati, Ruiz, Sallée, Slangen, and Yu, 2021; Garner, Kopp, Hermans, Slangen, Koubbe, Turilli, Jha, Edwards, Levermann, Nowicki, Palmer, and Smith, in prep.). This tool visualizes the median projections of global and regional sea level rise, relative to a 1995-2014 baseline. These projections are based on IPCC (2023). We source the data for the region IJmuiden, a port city in the Dutch province of North Holland.[27] By the end of the century, this region is expected to experience a sea level rise of 0.59 meters under an intermediate greenhouse gas emission scenario (SSP2-4.5). The evolution of climate risk is depicted in Figure 2.1 under the different SSP$x-y$ trajectories. It indicates that more severe global warming scenarios put more houses at risk of flooding.

[24] These are reported for the Netherlands as of 2010, or based on the terminal values in Van der Straten (2023).

[25] Since agents are financially risk neutral, we only need to specify the risk-free rate of interest, r. Since the risk free rate of interest is reported for a period of 30 years, the corresponding annual rate is equal to to $(1+0.718)^{1/30}-1=1.18\%$.

[26] Bosker et al. (2019) provides estimates of the number of the currently flood safe houses that a future rise in sea levels would put at risk of flooding in a best-, medium-, and worst-case scenario with sea levels rising by 24, 100 or 150 cm respectively, based on Dutch elevation data.

[27] While regional projections are provided for various Dutch regions, there is relatively little variability in their projection. Projections are provided for the regions Vlissingen, Roompot Buiten, Hoek van Holland, Maassluis, Ijmuiden, Den Helder, West-Terschelling, Harlingen, Delfzijl and Borkum.

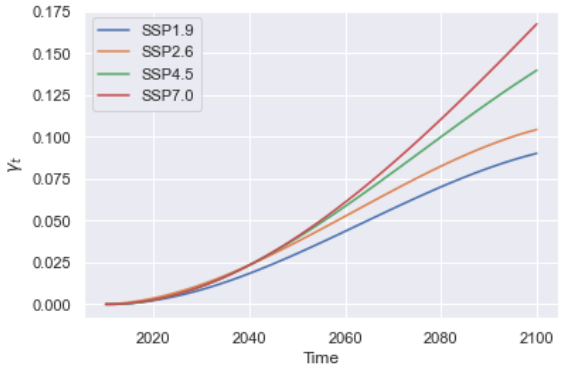


Figure 3.6.2: **Evolution of the share of flood-safe houses that future sea level rise puts at risk of flooding (γ_t) under the distinct SSP$x-y$ trajectories.**

Finally, the functional form specifications are given by $v(L) = ln(L)$ and $f(\bar{L}) = ln(\bar{L})$

3.6.1 Results

We provide the results under an initial stage without public adaptation, $X_t = 0$. We conduct counterfactual analysis under various climate change scenarios. Since the climate change scenarios of projected socioeconomic global changes are available up to the year 2100, we assume that a steady state is reached at that point and solve the model backwards from then on.

Evolution of the Housing Stock and House Prices

The supply of inhabitable houses falls exogenously in the model with climate risk, leading to a reduction in the housing stock by approximately 25 percent at the end of the century in the SSP3-7.0 trajectory (see left panel of Figure 3.6.3). In accordance with Van der Straten (2023), the rising scarcity of habitable land translates into a sharp rise of house prices over time (right panel, Figure 3.6.3).

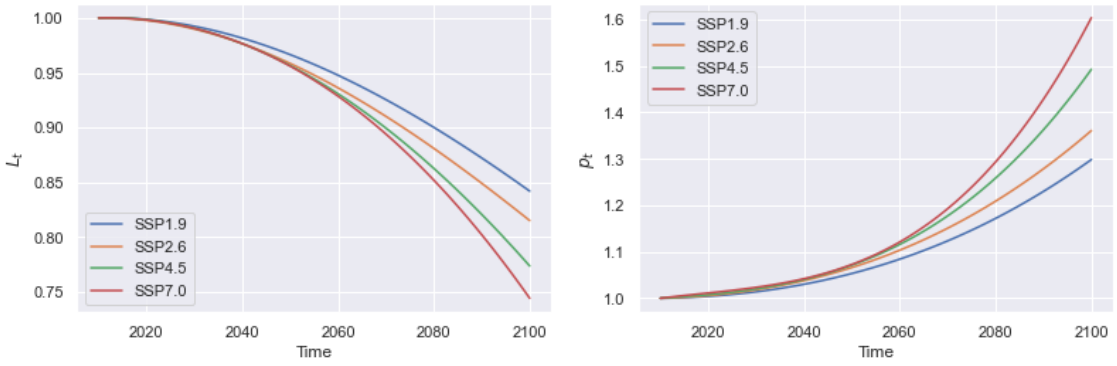


Figure 3.6.3: **Evolution of the housing stock and housing prices**

Key: The steady-state of supply of inhabitable houses (left panel, indexed to 1 in 2010) and house prices (right panel, indexed to 1 in 2010) for different SSP$x-y$ trajectories.

Evolution of the Political Equilibrium

The political equilibrium depends on the level of disagreement between realists and skeptics. A coalition between young skeptics and old realists only forms when their beliefs are sufficiently dispersed, but not too dispersed. Figure 3.6.4 illustrates the time paths of the upper and lower limits on belief dispersion (denoted as Θ) for which a coalition of young skeptics and old realists is stable, under different SSP$x-y$ scenarios. Assumption 1 sets the lower bound on Θ, representing the minimum level of belief dispersion at which old realists prefer to join forces with young skeptics rather than old skeptics. The blue-shaded area in the figure shows where Assumption 1 is *not* met, meaning that the belief gap isn't wide enough to make old realists' adaptation rate higher than that preferred by young skeptics. In this case, old realists would rather form a coalition with old skeptics. Hence, the political equilibrium that emerges is a coalition of the old.

In contrast, the pink- and yellow-shaded areas highlight regions where Assumption 1 is satisfied. Here, the belief dispersion is sufficient for old realists to prefer a coalition with young skeptics, as their adaptation rate is higher than the one preferred by old skeptics. Old optimists are then strictly better off if they form a coalition with young pessimists. Proposition 1 provides the upper limit for Θ, defining the maximum level of belief dispersion at which young skeptics still prefer allying with old realists over

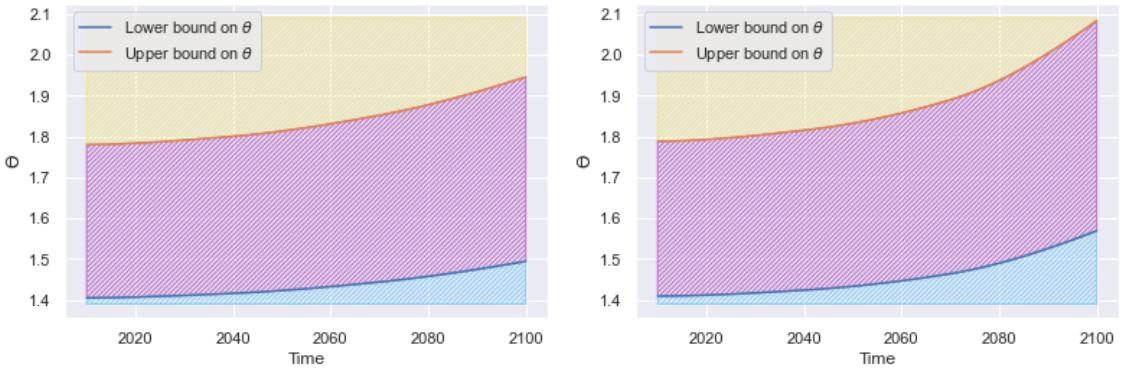


Figure 3.6.4: **Evolution of the political equilibrium**

Key: Joint evolution of the upper (Proposition 2) and lower (Assumption 3) bounds on dispersion in beliefs for which a coalition of young pessimists and old optimists prevails (pink-shaded area). The left panel shows the evolution of the bounds under SSP1-2.6 and the right panel shows the evolution of the bounds under SSP3-7.0.

old skeptics.[28] The yellow-shaded area shows where the condition in Proposition 1 is *not* met, meaning young skeptics would prefer to form a coalition with old skeptics. The pink-shaded areas, on the other hand, show where the condition is met, and where Assumption 1 holds. In this region, young skeptics gain more utility by forming a coalition with old realists.

As climate risk intensifies, the region where Assumption 1 is satisfied becomes smaller, both over time and for more adverse climate change scenarios. This happens because climate change—driven habitat loss raises house prices and thereby the value of public adaptation. This, in turn, increases the preferred adaptation rate of young skeptics relative to that of the old. Therefore, the belief dispersion must grow larger to overcome the effect of rising house prices and ensure our coalitions remain internally stable.

At the same time, as house prices rise, the preferred adaptation rate of young skeptics increases, making them more likely to favor a coalition with old realists rather than old skeptics. This weakens the condition in Proposition 1, causing the upper bound on belief dispersion to rise. In other words, this coalition remains internally stable for

[28] If utility of young pessimists, $\mathbb{E}_t(U^{Ys})$ is symmetric around the optimal adaptation rate, τ_t^{Ys*}, the bound in Proposition 2 can be approximated by $\tau_t^{Ys,Or} - \tau_t^{Ys*} \leq \tau_t^{Ys*} - \tau_t^{Ys,Os}$. We use this approximation in Figure 3.6.4.

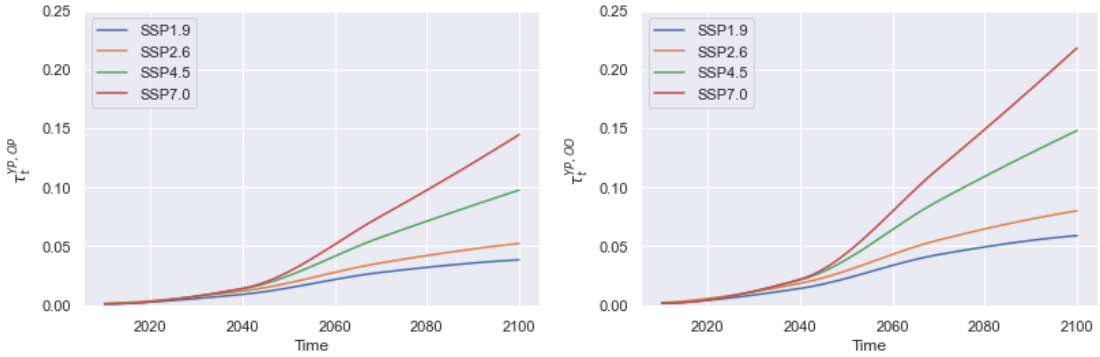


Figure 3.6.5: **Adaptation rates proposed by different coalitions**

Key: The adaptation rate proposed by a coalition of pessimists (left panel) and a coalition of young pessimists and old optimists (right panel) for different SSP trajectories.

larger levels of belief dispersion over time. As a result, the region where a coalition of young skeptics and old realists dominates expands, especially as climate risk becomes more urgent and for more adverse climate change scenarios.

Political Tipping in Adaptation Rates

Using the insights from Figure 3.6.4, we focus on a value for the dispersion in beliefs, Θ, such that the political equilibrium tips. Figure 3.6.5 shows the time paths of the adaptation rates proposed by each coalition. The adaptation rates proposed by the majority coalition is illustrated by a solid line at each point in time. The proposed adaptation rates rise as climate risk increases over time. However, the outcome of the political process crucially matters for the level of public adaptation, as the adaptation rate proposed by a coalition of young skeptics and old realists is consistently higher than the rate proposed by a coalition of skeptics.

Under the current specification of beliefs, the political equilibrium shifts from a coalition of only skeptics to a coalition of young skeptics and old realists around 2070. This tipping point marks a pivotal change in the proposed adaptation rate. As shown in Figure 3.6.6, the quantitative impact of this political shift becomes more pronounced as climate change intensifies. Consequently, it significantly shapes the overall adaptation strategy, precisely when the need for adaptation is greatest.

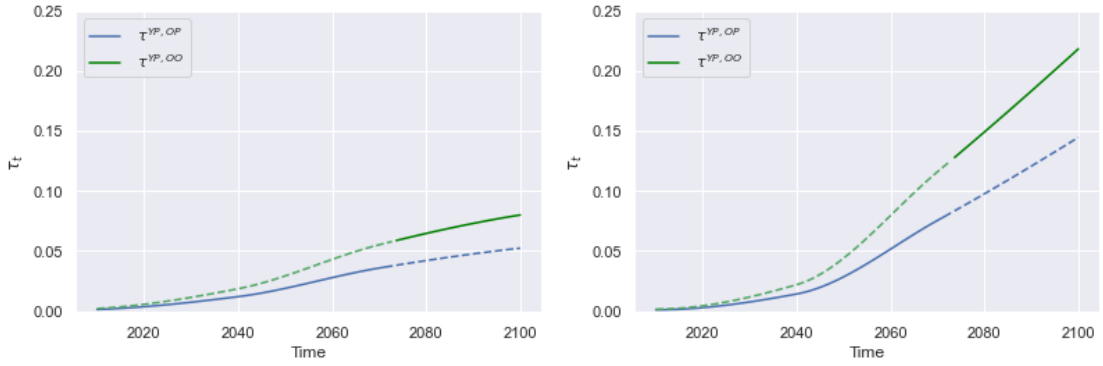


Figure 3.6.6: **Political tipping**

Key: The prevailing adaptation rate in the economy over time over time when the political equilibrium tips around 2070, under SSP1-2.6 (left panel) and SSP3-7.0 (right panel).

3.7 Public Adaptation Gap

To compare the political economy equilibrium to the social optimum, we determine the optimal public policy where X_t is chosen to maximize utilitarian social welfare. We first consider the case in which the social optimum is determined with realistic perceptions on the severity of climate risk only, i.e., $\theta_j = 1, \forall j$. We also consider a social optimum in which the dispersion in beliefs is accounted for.

$$\begin{aligned} \max_{X_{G,t}} \sum_{t=0}^{\infty} \left(\frac{1}{1+r}\right)^t \left((1+r)\left((1-\tau_t)\left[\phi q + (1-\phi)w\right]\right) + v(\bar{L}_t) + f(\bar{L}_{t+1})\right) \\ s.t. \quad \frac{1}{2} X_{G,t}^{2*} \bar{L}_t = \tau_t \cdot \left[\phi q + (1-\phi)\, w\right] \\ \bar{L}_j = \bar{L}_t \prod_{\iota=t}^{j-1} \left(1 - (1 - X_{G,\iota})\, \mu \gamma_{\iota+1}\right). \end{aligned} \tag{3.7.41}$$

Proposition 2. *The socially optimal level of public adaptation equals*

$$X_t^* = \frac{\mu_L \gamma_{t+1}}{(1+r)} \cdot \sum_{j=t+1}^{\infty} \left(\frac{1}{1+r}\right)^{j-t} \left[-\frac{1}{2}(1+r)X_j^2 + v'(\bar{L}_j)\right] \prod_{\iota=t+1}^{j-1} \left(1-(1-X_\iota)\,\mu_L \gamma_{\iota+1}\right)$$
$$+ \left(f'\left(\bar{L}_{t+1}\right) + \sum_{j=t+1}^{\infty} \left(\frac{1}{1+r}\right)^{j-t} \left(f'(\bar{L}_{j+1})\right) \prod_{\iota=t+1}^{j} \left(1-(1-X_\iota)\,\mu_L \gamma_{\iota+1}\right)\right). \quad (3.7.42)$$

Proof: See Appendix A1.C.

A comparison between the socially optimal adaptation rate with the preferred adaptation rate of the young and old reveals that the socially optimal adaptation rate is higher. Households thus do not fully internalize the benefits of public adaptation. Since the old do not own housing capital, they do not respond to price incentives and thus do not take into consideration that public adaptation reduces the speed at which habitat shrinks. While the young partially internalize the impact of public adaptation on the evolution of the housing stock – through its capitalization into house prices (Van der Straten, 2023) – the horizon they internalize remains limited. Specifically, they fail to account for the fact that preserving housing benefits *all* future generations, not just their off-springs. In contrast, under the social optimum, the benefits associated with public adaptation are fully internalized across *each* subsequent generation. Hence, the private choice of adaptation does not equal the social optimum – even if all households were to have realistic perceptions on the severity of climate risk ($\theta_j = 1, \forall j$).

To quantify the public adaptation gap, we compare the socially optimal adaptation rate with the adaptation rates proposed by the prevailing coalitions over time. Figure 3.7.7 illustrates the evolution of this gap, with each panel corresponding to a distinct SSP$x-y$ trajectory. The blue line represents the socially optimal adaptation rate, determined under realistic perceptions of the efficacy of public policy. The green line depicts the adaptation rate set by a coalition of skeptics, while the red line shows the adaptation rate chosen after the political equilibrium shifts to a coalition of young skeptics and old realists. The public adaptation gap is visualized by the purple and orange shaded areas between these lines at any given time. A significant part of the adaptation gap

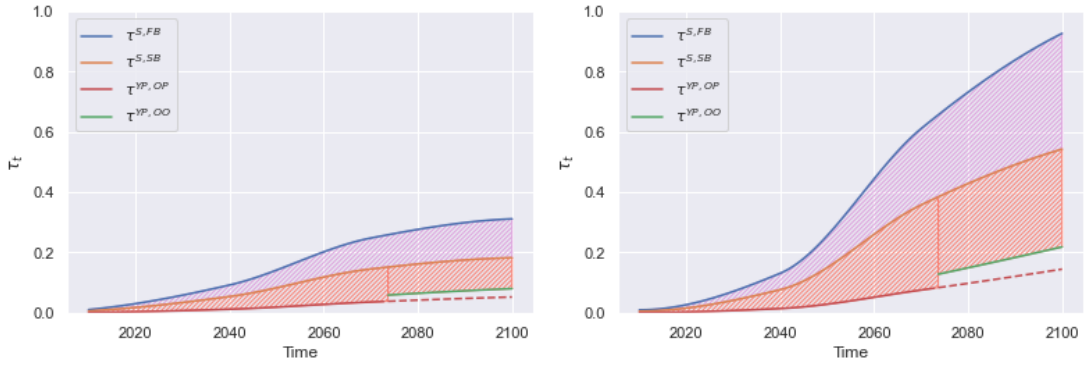


Figure 3.7.7: **Decomposition of the public adaptation gap**

Key: Evolution of the time path of the adaptation gap (orange- and purple-shaded area) and the adaptation gap in the case in which the beliefs about the efficacy of public intervention are taken into account (orange-shaded area). The results are shown under SSP1-2.6 4.5 (left) and SSP3.-7.0 (right panel).

arises from skepticism about the efficacy of public policy (purple-shaded area). However, even if all households shared realistic perceptions of, a residual adaptation gap would persist. This is because households primarily value the present and near-term supply of habitable land, failing to internalize the long-term benefits of public adaptation for future generations .

To decompose the adaptation gap, we also compute the optimal adaptation rate under the assumption that dispersion in political beliefs is fully accounted for (see Appendix A.1.C), which is represented by the orange line in Figure 3.7.7. The orange-shaded area corresponds to the "tragedy of the horizon" effect, highlighting the gap caused by the short-term focus of individual households. While skeptical political beliefs explain a significant share of the adaptation gap, the tragedy of the horizon effect remains a substantial contributor. Over time, the adaptation gap widens further at an accelerating rate as the supply of habitable land diminishes. While this increases the urgency for public adaptation to preserve land for all future generations, the prevailing coalitions fall short of internalizing, and thus addressing, this increasing need.

3.8 The Role of Income Inequality

We provide an extension of our analysis in which old households know their income level and adjust their preferences over adaptation based on their income and beliefs. This distinction matters for voting outcomes and consequently affects the political equilibrium that prevails.

3.8.1 Old Households' Choice of Adaptation Rate

An old household, with beliefs $j \in \{r, s\}$ and income $y \in \{q, w\}$ maximizes

$$\begin{aligned} \max_{\tau_t} \mathbb{E}\left(U\left(c_{i,t},, \bar{L}_j, t+1\right)\right) &= \mathbb{E}_{j,t}\left(c_{i,t}\right) + f\left(\mathbb{E}_{j,t}\left(\bar{L}_{t+1}\right)\right) \\ s.t. \quad c_{i,t} &\leq \left(1-\tau_t\right) y_i + \max\left\{p_t\left(1-\xi_{i,t}\right) L_{i,t-1} + \left(1+\hat{r}\right) S_{i,t-1}, 0\right\} \\ \tau_t &\geq 0. \end{aligned} \tag{3.8.43}$$

Lemma 5. *The optimal adaptation rate of an old household with beliefs θ_j and income y is*

$$\tau_t^{O,i,j*} = \frac{1}{\bar{L}_t} \cdot \left[\phi q + (1-\phi) w\right] \cdot \left(\frac{\mu \cdot \theta_{j,t} \cdot \gamma_{t+1} \cdot \pi_{j,t}}{y_i}\right)^2 \tag{3.8.44}$$

If the wage gap is smaller than the dispersion in beliefs (scaled by the marginal utilities of the future housing stock), i.e.,

$$\frac{q}{w} < \frac{\theta_{r,t}}{\theta_{s,t}} \cdot \frac{\pi_{r,t}}{\pi_{s,t}} \tag{3.8.45}$$

then we have

$$\tau^{O,r,l*} > \tau^{O,r,h*} > \tau^{O,s,l*} > \tau^{O,s,h*}.$$

Otherwise, we have

$$\tau^{O,r,l*} > \tau^{O,s,l*} > \tau^{O,r,h*} > \tau^{O,s,h*}.$$

Since the present investment in adaptation does not benefit the old households directly any longer, the difference in the preferred adaptation rates of high- respectively low-income households is fully explained by differences in wages. As low-income, old households bear an smaller fraction of the investment costs associated with public adaptation, due to the proportionality of taxes, they favour a higher adaptation rate than high-income households.

3.8.2 Feasible Coalitions

Income is a distinguishing factor among old households, influencing the preferred adaptation rate of the old. As a consequence, the voting preferences of the old household groups now also depends on their income type and coalitions must include (at least) three groups of households to form a majority. We summarize the set of feasible coalitions, and the adaptation rates that maximize the joint utility of each coalition, in Lemma A1 in Appendix A2.F.

The wage gap, which determines the relative ordering of the adaptation rates preferred by the various groups of old households (see Lemma 5), also affects the set of feasible coalitions. In particular, a rise in economic inequality, as reflected by an increase in the wage gap, q/w, increases the adaptation rate preferred by the low-income, old skeptics relative to the adaptation rate preferred by the high-income, old realists.[29] This is because the relative reduction in their income lowers fraction of the investment costs which are borne by the low-income households. Consequently, if the wage gap is sufficiently large, the preferences of pivotal voters align more closely with those of the low-income, old skeptics than with their previous coalition partners – the high-

[29] If economic inequality declines, this does not lead to a change in the relative ordering of the preferred adaptation rates of the old, unless economic inequality is very large at the onset. If the latter is the case, the political equilibrium tips between the same coalitions as outlined below, although in reverse order.

income, old realists. As a result, old skeptics become relevant in the formation of majority coalitions. This highlights how rising economic inequality reshapes the political equilibrium.

3.8.3 Evolution of the Political Equilibrium and Equilibrium Tipping

While some coalitions are politically feasible, the political equilibrium that emerges depends on the preferences of young skeptics. We evaluate the viability of the most ambitious coalition, determining the conditions under which young skeptics prefer to form a coalition which leads to the highest attainable adaptation rate within our environment. If beliefs are not too dispersed, an equilibrium exists in which the economy tips to a political equilibrium characterized by the prevailing of this "high-ambition" coalition (see Proof of Proposition A2, in Appendix A1.C).

To study the evolution of the political equilibrium over time, we use a comparable parameterization as for the baseline model. With regards to wages, we start from a case in which the wages of high- and low-income workers are equal, and reduce the wage of low-income workers disproportionately over time to reflect rising inequality. We let inequality increase gradually over time, picking up speed temporarily during the mid of the century.[30] We also show the results in the case the rise in the inequality accelerates in Appendix A3.B.

The evolution of the political equilibrium is displayed in Figure **??**, in Appendix A3.A. The panels reveal that the coalition of young skeptics and old realists prevails until 2060, after which the political equilibrium shifts to a less ambition coalition. Once inequality is

[30] The evolution of inequality, to which we fit an S-curve, is plotted in Figure 3.13.9 in Appendix A3.A.

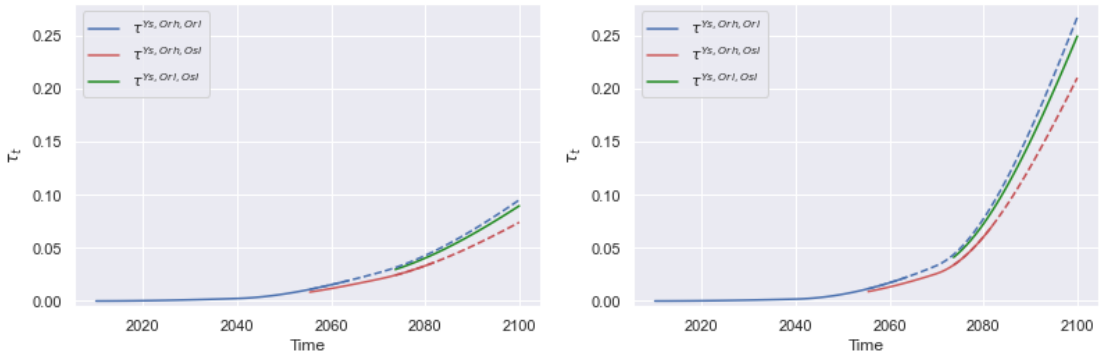


Figure 3.8.8: **Tipping of the adaptation rate**

Key: The time path for the adaptation rate when the political equilibrium tips around 2050, and 2080, under SSP1-2.6 (left panel) and SSP3-7.0 (right panel).

sufficiently high (see Lemma 5), the political equilibrium tips around 2080 to the high-ambition coalition, which includes the young skeptics and low-income, old.

Political tipping again affects the prevailing adaptation rate, as shown in Figure 3.8.8. While the prevailing adaptation rate is higher after the second tipping point than in the case in which the political equilibrium does not tip, the prevailing adaptation rate is lower compared to the case in which inequality remains constant over time. The political backlash occurs due to tension between beliefs and income. Specifically, the low-income old skeptics enter the new majority coalition, replacing the high-income old realists. If inequality rises gradually, the difference in income between the groups of old households is not sufficient to offset the inclusion of a larger number of skeptics in the majority coalition. Hence, political tipping leads to *less* spending on public intervention in this case.

Escalating inequality

Figure 3.13.11 in Appendix A3.B shows that the effect of the tipping point on the adaptation rate depends crucially on the rate at which economic inequality rises. Specifically, if economic inequality rises at an accelerating rate, the effect of income on the adaptation rate dominates the effect due to skeptic beliefs. Then, the second tipping point leads to *more* public intervention. Thus, our findings indicate that economic inequality

plays a critical role in shaping the political feasibility of climate policy, highlighting the importance of addressing inequality to effectively contain the damages from climate change.

3.8.4 Rising Inequality and the Young

In our extension, old households know their income level and adjust their preferences accordingly, while the young remained under the Rawlsian veal of ignorance. However, as inequality rises, the young may view it more likely that they will be of the low-income type. While this does not change the composition of the political equilibrium that emerges, it does affect the speed at which the political equilibrium tips. As young households view it more likely that they are of the low-income type, their preferred adaptation rate rises.[31] Consequently, the preferences for adaptation of the young skeptics converge to those of the old realists, and diverge from those the old skeptics. Then, for relatively lower levels of climate risk, the young skeptics prefer to form a coalition with the old realists.

Corollary 1. *If young households view it more likely that they are of the low-income type, the first political tipping point occurs sooner.*

The timing of the second tipping point depends entirely on the evolution of the wage gap and how it's size compares to the dispersion in beliefs. Hence, the timing of the second tipping point remains unaffected by a change in the perceived probability of being of the low income type.

Corollary 2. *If young households view it more likely that they are of the low-income type, the likelihood that the second tipping point occurs increases, but its timing remains unaffected.*

[31] Suppose the young's perceived probability of being of the low-income type is $(1-\phi+\epsilon)$ with $\epsilon \in (0,\phi)$. Then, the preferred adaptation rate of a young household with beliefs θ_j becomes

$$\tau_t^{Ys*} = \frac{(\mu\gamma_{t+1})^2}{\bar{L}_t} \cdot \frac{[\phi q + (1-\phi)\, w]}{[(\phi-\epsilon)q + (1-\phi+\epsilon)\, w]^2} \cdot \left(\frac{\tilde{\theta}_{j,t} \cdot (p_{t+1} + \pi_{s,t})}{(1+r)}\right)^2$$

3.9 Conclusion

We study the evolution of political support for preventive measures against the impact of climate change. We focus on the collective impact of climate change, recognizing how extreme events and rising temperature exacerbates land degradation through increasing floods, erosion, soil salinity, landslides, and sea level rise. As a result, previously habitable land becomes unsuitable for development, thus negatively affecting its long-term usability.

Political preferences are shaped by age, income and belief; over time they are affected by rising climate risk and economic inequality. Modelling these trends allows to analyze changing policy attitudes. Rising physical climate risks strengthens incentives even for skeptical voters to make compromises and agree to public intervention. At the same time, rising economic inequality also affect voter views on the role for public investment in protective infrastructure, but may lead to political backlash.

Next to differences in age and income, we study the role of different beliefs. In the main model we focus on voter skepticism about the efficacy of climate adaptation, showing its major effect on the adaptation rate. If beliefs are sufficiently polarized, the subgroup of skeptic young household turns out to be pivotal. As long as climate risk is modest, these skeptic young households support only modest investment in public adaptation.

Our political economy analysis highlights the possibility of political tipping, which occurs when the prevailing coalition changes due to gradual climate change. Rising climate risk increases support for public adaptation, as more scarce habitat increases house prices and the value of preventive measures. Critically, the preferred adaptation rate of young skeptics rises at a faster rate than their political allies. When the beliefs on the efficacy of public adaptation are not too polarized, the political equilibrium eventually tips from a coalition of skeptics to a coalition of young skeptics and old realists willing to will spend more on climate change adaptation.

While political tipping increases public adaptation, the shift does not manage to

internalize its broader societal value. The outcome of the political process yields an adaptation rate that is lower than the social optimum. This is in part due to skepticism about the efficacy of the public intervention. Moreover, as the political process only affects the present and near future, it fails to internalize the benefits of public adaptation for all future generations. This "tragedy of the horizon" effect inevitably associated with the political process undermines public investments in flood protection, and prevents adaptation from catching up with the long-term social optimum.

In an extension, we consider the role of income inequality. We show that a steady rise in inequality ultimately induces a second political tipping point, towards a coalition of low-income old and the young skeptics. When inequality increases gradually, this tipping point reduces the politically feasible level of flood protection, which illustrates the tension between economic inequality and climate policy. Moreover, this highlights the importance of redistributive policies to effectively contain the damages from climate change.

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Appendix

3.11 Proof of Propositions

3.11.1 Proof of Proposition A1

Proposition 3. *Suppose climate risk, γ rises in all future periods by a factor $\zeta > 1$, so that $\{\zeta\gamma_{t+1}, ..., \zeta\gamma_{\infty}\}$. Then, house prices rise in this factor ζ if*

$$-\frac{\frac{\partial v'(\bar{L}_j)}{\partial \bar{L}_j} \cdot \mathbb{E}\left(\bar{L}_j\right)}{v'\left(\bar{L}_j\right)} \cdot \frac{\sum_{\iota=t}^{j-1} X_{\iota}^{*} \gamma_{\iota+1} \cdot \prod_{\iota'=t,\iota'\neq\iota}^{j-1} \left(1-\left(1-X_{\iota'}^{*}\right)\mu\zeta \cdot \gamma_{\iota'+1}\right)}{\sum_{\iota=t}^{j-1} \int_0^1 X_{\iota}^{*}\theta_{j,\iota}di \cdot \gamma_{\iota+1} \cdot \prod_{\iota'=t,\iota'\neq\iota}^{j-1} \left(1-\left(1-X_{\iota'}^{*}\right)\mu\zeta \cdot \int_0^1 \theta_i di \gamma_{\iota'+1}\right)} \geq 1. \tag{3.11.46}$$

This condition becomes more stringent in $\int_0^1 \theta_{j,\iota}di$ and for $\int_0^1 \theta_{j,\iota}di = 1$, this condition is equivalent as in Van der Straten (2023).

The price of housing capital in a given period, t, is given by

$$p_t^{*} = \frac{\left(1-\left(1-X_t^{*}\right)\mu \int_0^1 \theta_{i,t}di \cdot \gamma_{t+1}\right) p_{t+1} + v'(\bar{L}_t)}{(1+r)} \tag{3.11.47}$$

Forward substitution gives

$$p_t^{*} = \sum_{j=t}^{\infty} \left(\frac{1}{1+r}\right)^{j-t+1} \left[v'\left(\bar{L}_j\right)\right] \prod_{\iota=t}^{j-1} \left(1-\left(1-X_t^{*}\right)\mu \int_0^1 \theta_{i,t}di \cdot \gamma_{\iota+1}\right) \tag{3.11.48}$$

where

$$\bar{L}_j = \bar{L}_t \prod_{\iota=t}^{j-1} \left(1-\left(1-X_t^{*}\right)\mu\gamma_{\iota+1}\right) \tag{3.11.49}$$

Suppose climate risk, γ, increases in all future periods, i.e. $\{\gamma_{t+1}, ..., \gamma_{\infty}\}$ by some factor $\zeta > 0$, i.e. $\{\zeta\gamma_t, ..., \zeta\gamma_{\infty}\}$. Then, the price of house capital is given by

$$p_t = \sum_{j=t}^{\infty} \left(\frac{1}{1+r}\right)^{j-t+1} \left[v'\left(\bar{L}_j\right)\right] \prod_{\iota=t}^{j-1} \left(1-\left(1-X_{\iota}^{*}\right)\mu\zeta \cdot \int_0^1 \theta_i di \gamma_{\iota+1}\right) \tag{3.11.50}$$

Then, the FOC of p_t with respect to ζ is given by

$$\frac{\partial p_t}{\partial \zeta} = \sum_{j=t}^{\infty} \left(\frac{1}{1+r}\right)^{j-t+1} \frac{\partial v'(\bar{L}_j)}{\partial \bar{L}_j} \cdot \frac{\partial \bar{L}_j}{\partial \zeta} \cdot \prod_{\iota=t}^{j-1} \left(1 - (1 - X_\iota^*)\, \mu\zeta \cdot \int_0^1 \theta_i di \gamma_{\iota+1}\right) \tag{3.11.51}$$
$$+ v'\left(\bar{L}_j\right) \cdot \frac{\partial}{\partial \zeta} \left(\prod_{\iota'=t}^{j-1} \left(1 - (1 - X_{\iota'}^*)\, \mu\zeta \cdot \int_0^1 \theta_i di \gamma_{\iota'+1}\right)\right)$$

where

$$\frac{\partial \bar{L}_j}{\partial \zeta} = -\mu \bar{L}_t \sum_{\iota=t}^{j-1} (1 - X_\iota^*) \gamma_{\iota+1} \prod_{\iota'=t, \iota' \neq \iota}^{j-1} (1 - (1 - X_{\iota'}^*)\, \mu\zeta \cdot \gamma_{\iota'+1}) \tag{3.11.52}$$

and

$$\frac{\partial}{\partial \zeta} \left(\prod_{\iota'=t}^{j-1} \left(1 - (1 - X_{\iota'}^*)\, \mu\zeta \cdot \int_0^1 \theta_i di \gamma_{\iota'+1}\right)\right) \tag{3.11.53}$$
$$= -\mu \int_0^1 \theta_i di \cdot \sum_{\iota=t}^{j-1} (1 - X_\iota^*)\, \gamma_{\iota+1} \cdot \prod_{\iota'=t, \iota' \neq \iota}^{j-1} \left(1 - (1 - X_{\iota'}^*)\, \mu\zeta \cdot \int_0^1 \theta_i di \gamma_{\iota'+1}\right)$$

Define

$$\mathbb{E}\left(\bar{L}_j\right) = \bar{L}_t \cdot \prod_{\iota=t}^{j-1} \left(1 - (1 - X_\iota^*)\, \mu \int_0^1 \theta_i di \cdot \gamma_{\iota+1}\right) \tag{3.11.54}$$

Then, this becomes

$$\frac{\partial p_t}{\partial \zeta} = -\mu \sum_{j=t}^{\infty} \left(\frac{1}{1+r}\right)^{j-t+1} \frac{\partial v'(\bar{L}_j)}{\partial \bar{L}_j} \cdot \mathbb{E}\left(\bar{L}_j\right) \cdot \sum_{\iota=t}^{j-1} (1 - X_\iota^*) \gamma_{\iota+1} \cdot \prod_{\iota'=t, \iota' \neq \iota}^{j-1} (1 - (1 - X_{\iota'}^*)\, \mu\zeta \cdot \gamma_{\iota'+1}) \tag{3.11.55}$$
$$+ v'\left(\bar{L}_j\right) \cdot \int_0^1 \theta_i di \cdot \sum_{\iota=t}^{j-1} (1 - X_\iota^*)\, \gamma_{\iota+1} \cdot \prod_{\iota'=t, \iota' \neq \iota}^{j-1} \left(1 - (1 - X_{\iota'}^*)\, \mu\zeta \cdot \int_0^1 \theta_i di \gamma_{\iota'+1}\right)$$

This is positive if

$$-\frac{\frac{\partial v'(\bar{L}_j)}{\partial \bar{L}_j} \cdot \mathbb{E}\left(\bar{L}_j\right)}{v'\left(\bar{L}_j\right)} \cdot \frac{\sum_{\iota=t}^{j-1}(1-X_\iota^*)\gamma_{\iota+1} \cdot \prod_{\iota'=t,\iota'\neq\iota}^{j-1}\left(1-\left(1-X_{\iota'}^*\right)\mu\zeta\cdot\gamma_{\iota'+1}\right)}{\sum_{\iota=t}^{j-1}\int_0^1\theta_i di\cdot\left(1-X_\iota^*\right)\gamma_{\iota+1}\cdot\prod_{\iota'=t,\iota'\neq\iota}^{j-1}\left(1-\left(1-X_{\iota'}^*\right)\mu\zeta\cdot\int_0^1\theta_i di\gamma_{\iota'+1}\right)} \geq 1 \tag{3.11.56}$$

Compare this with the condition under which house prices rise in Van der Straten (2023), i.e.

$$-\frac{\frac{\partial v'(\bar{L}_j)}{\partial \bar{L}_j}\cdot\bar{L}_j}{v'(\bar{L}_j)} \geq 1$$

The derived condition is less stringent than the one in Van der Straten (2023) if

$$\frac{\bar{L}_j}{\mathbb{E}\left(\bar{L}_j\right)} \leq \frac{\sum_{\iota=t}^{j-1}(1-X_\iota^*)\gamma_{\iota+1}\cdot\prod_{\iota'=t,\iota'\neq\iota}^{j-1}\left(1-\left(1-X_{\iota'}^*\right)\mu\zeta\cdot\gamma_{\iota'+1}\right)}{\sum_{\iota=t}^{j-1}\int_0^1\theta_i di\cdot(1-X_\iota^*)\gamma_{\iota+1})\cdot\prod_{\iota'=t,\iota'\neq\iota}^{j-1}\left(1-\left(1-X_{\iota'}^*\right)\mu\zeta\cdot\int_0^1\theta_i di\gamma_{\iota'+1}\right)} \tag{3.11.57}$$

This becomes

$$\sum_{\iota=t}^{j-1}\left(\frac{\int_0^1\theta_i di\cdot\left(1-X_\iota^*\right)\gamma_{\iota+1}}{\left(1-\left(1-X_\iota^*\right)\mu\zeta\cdot\int_0^1\theta_i di\gamma_{\iota+1}\right)}\right) \leq \sum_{\iota=t}^{j-1}\left(\frac{(1-X_\iota^*)\gamma_{\iota+1}}{(1-(1-X_\iota^*)\mu\zeta\cdot\gamma_{\iota+1})}\right) \tag{3.11.58}$$

which is always satisfied as $\int_0^1\theta_i di \leq 1$.

3.11.2 Proof of Proposition 1

Young skeptics prefer to form a coalition with old realists rather than old skeptics if

$$\mathbb{E}_t\left(U_{Ys}\left(\tau^{Ys,Or*}\right)\right) > \mathbb{E}_t\left(U_{Ys}\left(\tau^{Ys,Os*}\right)\right) \tag{3.11.59}$$

Using that

$$v'\left(L_{Ys,t}\right) = (1+r)p_t - \left(1-(1-X_t)\,\mu\tilde{\theta}_{Ys,t}\cdot\gamma_{t+1}\right)p_{t+1}$$

and assuming $v\left(L_{i,t}\right) = ln\left(L_{it}\right)$, the relevant condition becomes

$$\begin{aligned}&\underbrace{v\left(L_{Ys,t}\left(\tau^{Ys,Or*}\right)\right) - v\left(L_{Ys,t}\left(\tau^{Ys,Os*}\right)\right)}_{(i)>0} \\ &+\underbrace{f\left(\mathbb{E}_{s,t}\left(\bar{L}_{t+1}\left(\tau^{Ys,Or*}\right)\right)\right) - f\left(\mathbb{E}_{s,t}\left(\bar{L}_{t+1}\left(\tau^{Ys,Os*}\right)\right)\right)}_{(ii)>0} \\ &> (1+r)\underbrace{\left(\tau^{Ys,Or*}-\tau^{Ys,Os*}\right)}_{(iii)>0}y_{Ys,t}\end{aligned} \tag{3.11.60}$$

Substituting the expressions for $\tau^{Ys,Or*}, \tau^{Ys,Os*}$ and rewriting gives

$$\begin{aligned}&\left(\frac{\left(\omega\cdot\tilde{\theta}_{s,t}p_{t+1}+\pi_{r,s,t}\cdot\left(\omega\cdot\tilde{\theta}_{s,t}+(1-\omega)\cdot\tilde{\theta}_{r,t}\right)\right)}{(1+\omega r)}\right)^2 - \left(\frac{\tilde{\theta}_{s,t}\cdot\left(\frac{1}{2}p_{t+1}+\pi_{s,t}\right)}{\left(1+\frac{1}{2}r\right)}\right)^2 \\ &< \frac{\bar{L}_t}{\left(\mu\gamma_{t+1}\right)^2}\cdot\frac{\Delta_\tau v\left(L_{Ys,t}\right)+\Delta_\tau f\left(\mathbb{E}_{s,t}\left(\bar{L}_{t+1}\right)\right)}{(1+r)}\end{aligned} \tag{3.11.61}$$

where

$$\Delta_\tau v\left(L_{Ys,t}\right) = v\left(L_{Ys,t}\left(\tau^{Ys,Or*}\right)\right) - v\left(L_{Ys,t}\left(\tau^{Ys,Os*}\right)\right),$$

and

$$\Delta_\tau f\left(\mathbb{E}_{s,t}\left(\bar{L}_{t+1}\right)\right) = f\left(\mathbb{E}_{s,t}\left(\bar{L}_{t+1}\left(\tau^{Ys,Or*}\right)\right)\right) - f\left(\mathbb{E}_{s,t}\left(\bar{L}_{t+1}\left(\tau^{Ys,Os*}\right)\right)\right).$$

Denote by

$$B \equiv B\left(\bar{L}_t, \gamma_{t+1}, \Delta_\tau v\left(L_{Ys,t}\right), \Delta_\tau f\left(\mathbb{E}_{s,t}\left(\bar{L}_{t+1}\right)\right)\right) = \frac{\bar{L}_t}{\left(\mu\gamma_{t+1}\right)^2} \cdot \frac{\Delta_\tau v\left(L_{Ys,t}\right) + \Delta_\tau f\left(\mathbb{E}_{s,t}\left(\bar{L}_{t+1}\right)\right)}{(1+r)}.$$

This allows us to rewrite the condition as

$$\frac{\omega^2}{(1+\omega r)^2} \cdot \left(p_{t+1} + \pi_{r,s,t} \cdot \left(1 + \frac{(1-\omega)}{\omega} \cdot \frac{\tilde{\theta}_{r,t}}{\tilde{\theta}_{s,t}}\right)\right)^2 < \frac{B}{\tilde{\theta}_{s,t}^2} + \frac{1}{\left(1+\frac{1}{2}r\right)^2} \cdot \left(\frac{1}{2}p_{t+1} + \pi_{s,t}\right)^2 \tag{3.11.62}$$

which can be simplified to obtain

$$p_{t+1} + \pi_{r,s,t} \cdot \left(1 + \frac{(1-\omega)}{\omega} \cdot \frac{\tilde{\theta}_{r,t}}{\tilde{\theta}_{s,t}}\right) < \frac{1+\omega r}{\omega} \cdot \sqrt{\left(\frac{B}{\tilde{\theta}_{s,t}^2} + \frac{1}{\left(1+\frac{1}{2}r\right)^2} \cdot \left(\frac{1}{2}p_{t+1} + \pi_{s,t}\right)^2\right)} \tag{3.11.63}$$

Then, young skeptics prefer to form a coalition with old realists if

$$\tilde{\Theta} < \left(\frac{1}{\pi_{r,s,t}}\left(\frac{1+\omega r}{(1-\omega)} \cdot \sqrt{\left(\frac{B}{\tilde{\theta}_{s,t}^2} + \frac{1}{\left(1+\frac{1}{2}r\right)^2} \cdot \left(\frac{1}{2}p_{t+1} + \pi\right)^2\right)} - p_{t+1}\right) - 1\right) \tag{3.11.64}$$

Otherwise, we have that

$$\mathbb{E}_t\left(U_{Ys}\left(\tau^{Ys,Or*}\right)\right) < \mathbb{E}_t\left(U_{Ys}\left(\tau^{Ys,Os*}\right)\right) \tag{3.11.65}$$

and a coalition of young skeptics and old skeptics prevails.

3.11.3 Proof of Proposition 2

In the social optimum, the severity of climate risk is fully internalized, i.e. $\theta_j = 1, \forall j$. Then, the optimal choice of public adaptation is determined by maximizing a utilitarian social welfare function, i.e.

$$\max_{X_t} \sum_{t=0}^{\infty} \left(\frac{1}{1+r}\right)^t \left((1+r)\left((1-\tau_t)\left[\phi q + (1-\phi)w\right]\right) + v(\bar{L}_t) + f\left(\bar{L}_{t+1}\right)\right) \tag{3.11.66}$$

$$s.t. \quad \frac{1}{2} X_t^{2*} \bar{L}_t = \tau_t \cdot [\phi q + (1-\phi)\, w]$$

$$\bar{L}_j = \bar{L}_t \prod_{\iota=t}^{j-1} \left(1 - (1 - X_\iota)\, \mu \gamma_{\iota+1}\right).$$

The first order condition for X_t is

$$(1+r) X_t^* \bar{L}_t = \mu \gamma_{t+1} \bar{L}_t \cdot f'\left(\bar{L}_{t+1}\right) \tag{3.11.67}$$

$$+ \sum_{j=t+1}^{\infty} \left(\frac{1}{1+r}\right)^{j-t} \left(\left[-\frac{1}{2}(1+r) X_j^2 + v'(\bar{L}_j)\right] \frac{\partial \bar{L}_j}{\partial X_t} + f'\left(\bar{L}_{j+1}\right) \cdot \frac{\partial \bar{L}_{j+1}}{\partial X_t}\right)$$

Using that

$$\frac{\partial \bar{L}_j}{\partial X_t} = \mu_L \gamma_{t+1} \cdot \bar{L}_t \prod_{\iota=t+1}^{j-1} \left(1 - (1 - X_\iota)\, \mu_L \gamma_{\iota+1}\right) \tag{3.11.68}$$

The socially optimal public choice of adaptation becomes

$$X_t^*|_{\theta_j=1 \forall j} = \frac{\mu_L \gamma_{t+1}}{(1+r)} \cdot \underbrace{\sum_{j=t+1}^{\infty} \left(\frac{1}{1+r}\right)^{j-t} \left[-\frac{1}{2}(1+r) X_j^2 + v'(\bar{L}_j)\right] \prod_{\iota=t+1}^{j-1} \left(1 - (1 - X_\iota)\, \mu_L \gamma_{\iota+1}\right)}_{p_{t+1}|\theta_j=1, \forall j} \tag{3.11.69}$$

$$+ \left(f'\left(\bar{L}_{j+1}\right) + \sum_{j=t+1}^{\infty} \left(\frac{1}{1+r}\right)^{j-t} \cdot f'\left(\bar{L}_{j+1}\right) \prod_{\iota=t+1}^{j} \left(1 - (1 - X_\iota)\, \mu_L \gamma_{\iota+1}\right)\right)$$

Decomposing the Adaptation Gap

We solve for the optimum in the case in which the heterogeneity in the perceptions about climate change are accounted for, i.e. $\theta_{j,t}$:

$$\max_{X_t} \sum_{t=0}^{\infty} \left(\frac{1}{1+r}\right)^t \left((1+r)\left((1-\tau_t)\left[\phi q + (1-\phi)w\right]\right) + v(\bar{L}_t) + f\left(\bar{L}_{t+1}\right)\right) \quad (3.11.70)$$

$$s.t. \quad \frac{1}{2} X_t^{2*} \bar{L}_t = \tau_t \cdot [\phi q + (1-\phi)\, w]$$

$$\mathbb{E}\left(\bar{L}_j\right) = \bar{L}_t \prod_{\iota=t}^{j-1} \left(1 - (1 - X_\iota)\, \mu \int_0^1 \theta_{i,t} di \cdot \gamma_{\iota+1}\right).$$

In this case, the optimal level of public adaptation is given by

$$X_t^* = \frac{\mu_L \int_0^1 \theta_{i,t} di \cdot \gamma_{t+1}}{(1+r)} \cdot \sum_{j=t+1}^{\infty} \left(\frac{1}{1+r}\right)^{j-t} \left[-\frac{1}{2}(1+r) X_j^2 + v'(\bar{L}_j)\right] \prod_{\iota=t+1}^{j-1} \left(1 - \cdot (1 - X_\iota)\, \mu_L \int_0^1 \theta_{i,t} di \cdot \gamma_{\iota+1}\right)$$
$$+ \left(f'\left(\bar{L}_{j+1}\right) + \sum_{j=t+1}^{\infty} \left(\frac{1}{1+r}\right)^{j-t} f'\left(\bar{L}_{j+1}\right) \prod_{\iota=t+1}^{j} \left(1 - (1 - X_\iota)\, \mu_L \int_0^1 \theta_{i,t} di \cdot \gamma_{\iota+1}\right)\right) \quad (3.11.71)$$

3.11.4 Proof of Proposition A2

Proposition 4. *Let there be less young than old, skeptics represent a majority ($\omega > 0.5$), high-income households are a minority ($\phi < 0.5$), Assumption 2(*) (see Lemma A1) is satisfied, $v(L_{j,t}) = ln(L_{j,t})$ and $f(\bar{L}_{t+1}) = ln(\bar{L}_{t+1})$. Then, if inequality is sufficiently low and*

$$\frac{1}{(1+\omega r)^2} \cdot \left(p_{t+1} + \left(1 + \frac{(1-\omega)}{\omega} \cdot \frac{\tilde{\theta}_{r,t}}{\tilde{\theta}_{s,t}}\right) \cdot \pi_{s,r,t}\right)^2 \quad (3.11.72)$$
$$- \left(\frac{[\phi q + (1-\phi)\, w]}{(1+\omega r)\, \phi \cdot q + (2+r)\omega\, (1-\phi) \cdot w}\right)^2$$
$$\cdot \left(p_{t+1} + \left((2-\phi) + \phi \cdot \frac{(1-\omega)}{\omega} \cdot \frac{\tilde{\theta}_{r,t}}{\tilde{\theta}_{s,t}}\right) \cdot \pi_{r,s,t}\right)^2$$
$$< \frac{\Delta v\left(L_{Ys,t}\right) + \Delta f\left(E_{P,t}\left(\bar{L}_{t+1}\right)\right)}{(1+r)} \cdot \frac{\bar{L}_t}{(\omega \cdot \tilde{\theta}_{s,t} \mu \gamma_{t+1})^2}$$

the political economy equilibrium is characterized by a coalition of young skeptics and old realists. The adaptation rate proposed by this coalition equals

$$\tau_t^{Ys,Orh,Orl*} = A \cdot \left(\frac{\omega \tilde{\theta}_{s,t} p_{t+1} + \left(\omega \cdot \tilde{\theta}_{s,t} + (1-\omega) \cdot \tilde{\theta}_{r,t}\right) \cdot \pi_{r,s,t}}{(1+\omega r)} \right)^2. \tag{3.11.73}$$

If economic inequality is high and it holds that

$$\begin{aligned} &\left(\frac{\left[p_{t+1} + \left((2-\phi) + \frac{(1-\omega)}{\omega} \cdot (1-\phi) \cdot \frac{\tilde{\theta}_{r,t}}{\tilde{\theta}_{s,t}} \right) \cdot \pi_{r,s,t} \right]}{\omega (1+r) \left[\phi q + (1-\phi) w \right] + (1-\phi) w} \right)^2 \\ &- \left(\frac{\left[p_{t+1} + \left((2-\phi) + \frac{(1-\omega)}{\omega} \cdot \phi \cdot \frac{\tilde{\theta}_{r,t}}{\tilde{\theta}_{s,t}} \right) \cdot \pi_{r,s,t} \right]}{(1+\omega r) \phi \cdot q + (2+r) \omega (1-\phi) \cdot w} \right)^2 \\ &< \frac{\Delta v \left(L_{Ys,t} \right) + \Delta f \left(E_{P,t} \left(\bar{L}_{t+1} \right) \right)}{(1+r) \cdot \left[\phi q + (1-\phi) w \right]} \cdot \frac{\bar{L}_t}{(\omega \cdot \tilde{\theta}_{s,t} \mu \gamma_{t+1})^2} \end{aligned} \tag{3.11.74}$$

the political economy equilibrium is characterized by a coalition of young pessimists and the low-income old. The adaptation rate proposed by this coalition equals

$$\tau_t^{Ys,Orl,Osl*} = A \cdot \left[\phi q + (1-\phi) w \right]^2 \cdot \left(\frac{\omega \cdot \tilde{\theta}_{s,t} p_{t+1} + \left(\omega (2-\phi) \cdot \tilde{\theta}_{s,t} + (1-\omega)(1-\phi) \cdot \tilde{\theta}_{r,t} \right) \cdot \pi_{s,r,t}}{\omega (1+r) \left[\phi q + (1-\phi) w \right] + (1-\phi) w} \right)^2. \tag{3.11.75}$$

Alternatively, Assumption 2 is not satisfied (in either case), the political economy equilibrium is characterized by the mixed coalition. Then, the adaptation rate proposed equals

$$\tau_t^{Ys,Orh,Osl*} = A \cdot \left[\phi q + (1-\phi) w \right]^2 \cdot \left(\frac{\omega \cdot \tilde{\theta}_{s,t} p_{t+1} + \left(\omega (2-\phi) \cdot \tilde{\theta}_{s,t} + (1-\omega) \phi \cdot \tilde{\theta}_{r,t} \right) \cdot \pi_{r,s,t}}{\omega \cdot (1+r) \cdot \left[\phi q + (1-\phi) w \right] + (1-\omega) \phi \cdot q + \omega (1-\phi) \cdot w} \right)^2. \tag{3.11.76}$$

Low Economic Inequality

Young skeptics prefer a coalition with high-income and low-income, old realists rather than high-income, old realists and low-income, old skeptics if

$$\mathbb{E}_t\left(U_{Ys}\left(\tau^{Ys,Orh,Orl*}\right)\right) > \mathbb{E}_t\left(U_{Ys}\left(\tau^{Ys,Orh,Osl*}\right)\right) \tag{3.11.77}$$

Using similar steps as in Proof of Proposition 2, the relevant condition become

$$\begin{aligned}
&\frac{1}{(1+\omega r)^2}\cdot\left(p_{t+1}+\left(1+\frac{(1-\omega)}{\omega}\cdot\frac{\tilde{\theta}_{r,t}}{\tilde{\theta}_{s,t}}\right)\cdot\pi_{s,r,t}\right)^2 \\
&-\left(\frac{[\phi q+(1-\phi)\,w]}{(1+\omega r)\,\phi\cdot q+(2+r)\omega\,(1-\phi)\cdot w}\right)^2 \\
&\cdot\left(p_{t+1}+\left((2-\phi)+\phi\cdot\frac{(1-\omega)}{\omega}\cdot\frac{\tilde{\theta}_{r,t}}{\tilde{\theta}_{s,t}}\right)\cdot\pi_{r,s,t}\right)^2 \\
&<\frac{\Delta v\left(L_{Ys,t}\right)+\Delta f\left(E_{P,t}\left(\bar{L}_{t+1}\right)\right)}{(1+r)}\cdot\frac{\bar{L}_t}{(\omega\cdot\tilde{\theta}_{s,t}\mu\gamma_{t+1})^2}
\end{aligned} \tag{3.11.78}$$

High Economic Inequality

Young skeptics prefer to prefer a coalition with low-income, old realists and low-income, old skeptics rather than high-income, old realists and low-income, old skeptics if

$$\mathbb{E}_t\left(U_{Ys}\left(\tau^{Ys,Orl,Osl*}\right)\right) > \mathbb{E}_t\left(U_{Ys}\left(\tau^{Ys,Orh,Osl*}\right)\right) \tag{3.11.79}$$

Using similar steps as in Proof of Proposition 2, the relevant condition becomes

$$\left(\frac{\left[p_{t+1} + \left((2-\phi) + \frac{(1-\omega)}{\omega} \cdot (1-\phi) \cdot \frac{\tilde{\theta}_{r,t}}{\tilde{\theta}_{s,t}} \right) \cdot \pi_{r,s,t} \right]}{\omega (1+r) [\phi q + (1-\phi) w] + (1-\phi) w} \right)^2 \tag{3.11.80}$$
$$- \left(\frac{\left[p_{t+1} + \left((2-\phi) + \frac{(1-\omega)}{\omega} \cdot \phi \cdot \frac{\tilde{\theta}_{r,t}}{\tilde{\theta}_{s,t}} \right) \cdot \pi_{r,s,t} \right]}{(1+\omega r) \phi \cdot q + (2+r) \omega (1-\phi) \cdot w} \right)^2$$
$$< \frac{\Delta v (L_{Ys,t}) + \Delta f (E_{P,t} (\bar{L}_{t+1}))}{(1+r) \cdot [\phi q + (1-\phi) w]} \cdot \frac{\bar{L}_t}{(\omega \cdot \tilde{\theta}_{s,t} \mu \gamma_{t+1})^2}$$

These conditions implicitly define an upper bound on the degree of dispersion in beliefs for which young skeptics prefer to form a coalition with high-income and low-income, old realists, respectively, low-income, old optimists and low-income, old pessimists. If this condition is not satisfied (in either case), a coalition of young skeptics, high-income, old realists, and low-income, old skeptics prevails.

3.12 Derivation of Lemmas

3.12.1 Derivation of Lemma 1

The demand for housing follows from the first order condition for housing, $L_{j,t}$.

3.12.2 Derivation of Lemma 2

Young Households

Young households favor a adaptation rate that maximizes their expected lifetime utility:

$$\max_{\tau_t} \mathbb{E}\left(U\left(L_{j,t}, c_{i,t+1}, X_t\right)\right) = v\left(L_{j,t}\right) + \mathbb{E}_{j,t}\left(c_{i,t+1}\right) + f\left(\mathbb{E}_{j,t}\left(\bar{L}_{t+1}\right)\right) \tag{3.12.81}$$

$$\begin{aligned} s.t. \quad & (1-\tau_t)\, y_{i,t} \leq p_t L_{j,t} + S_{i,t} \\ & c_{i,t+1} \leq (1-\tau_{t+1})\, y_i + \max\left\{ p_{t+1}\left(1-\xi_{i,t+1}\right) L_{j,t} + (1+\hat{r})\, S_{i,t}, 0 \right\} \\ & \tau_t \geq 0 \end{aligned}$$

where $c_{i,t+1}$ is consumption of household i in period $t+1$ and $\mathbb{E}_t$ denotes expectations formed at date t.

Given the probability of default, the expectation of household i's consumption in period $t+1$, $c_{i,t+1}$, as formed at date t, becomes:

$$\mathbb{E}_t\left(c_{i,t+1}\right) = G\left(\hat{\xi}_{i,t+1}\right)\left(p_{t+1}\left(1-\mathbb{E}\left(\xi_{i,t+1} | \xi_{t+1} \leq \hat{\xi}_{i,t+1}\right)\right) L_{j,t} + (1+\hat{r}) S_{i,t}\right) \tag{3.12.82}$$

No arbitrage requires that the expected payoff of holding household debt to be equal to the riskless return earned on savings:

$$(1+r)(-S_{i,t}) = G\left(\hat{\xi}_{i,t+1}\right)(1+\hat{r})(-S_{i,t}) + \left(1-G\left(\hat{\xi}_{i,t+1}\right)\right) p_{t+1}\left(1-\mathbb{E}\left(\xi_{i,t+1} | \xi_{i,t+1} > \hat{\xi}_{i,t+1}\right)\right) L_{j,t} \tag{3.12.83}$$

where the expected payoff of holding household debt is equal to the repayment of the loan with interest in case the household does not default and the revenue from selling the collateral in case of default. Then, the expectation of household i's consumption in period $t+1$, $c_{i,t+1}$, as formed at date t, becomes

$$\mathbb{E}_{j,t}\left(c_{i,t+1}\right) = (1+r)(S_{i,t}) + p_{t+1}\left(1-\mathbb{E}_{j,t}\left(\xi_{i,t+1}\right)\right) L_{j,t} \tag{3.12.84}$$

Using that $\mathbb{E}_{j,t}\left(\xi_{i,t+1}\right) = \left(1 - X_t\right)\mu \cdot \theta_{j,t}\gamma_{t+1}$, the household optimization problem can be written as

$$\begin{aligned}\max_{\tau_t} \mathbb{E}\left(U\left(L_{j,t}, c_{i,t+1}, X_t\right)\right) = (1+r)\left(\left(1-\tau_t\right)y_{i,t} - p_t L_{j,t}\right) \\ + p_{t+1}\left(1-\left(1-X_t\right)\mu\theta_{j,t}\cdot\gamma_{t+1}\right)L_{j,t} + v\left(L_{j,t}\right) + f\left(\mathbb{E}_{j,t}\left(\bar{L}_{t+1}\right)\right) \\ s.t. \quad \tau_t \geq 0\end{aligned} \tag{3.12.85}$$

We abstract from path-dependency in public policy (i.e. $\partial\tau_{t+1}/\partial\tau_t = 0$). Moreover, we define

$$\pi_{j,t} \equiv f(\mathbb{E}_{j,t}(\cdot))/\partial\,\mathbb{E}_{j,t}(\cdot) \tag{3.12.86}$$

and, for notational simplicity, we denote by $\tilde{\theta}_{j,t}$ the belief-weighted landholdings exposure of household j at time t. Then, the FOC for τ_t is given by

$$\begin{aligned}-(1+r)y_{i,t} + \mu\tilde{\theta}_{j,t}\cdot\gamma_{t+1}\cdot\left(p_{t+1}+\pi_{j,t}\right)\cdot\frac{\partial X_t}{\partial\tau_t} + \\ \underbrace{\left[-(1+r)p_t\cdot + p_{t+1}\left(1-\left(1-X_t\right)\mu\theta_j\cdot\gamma_{t+1}\right) + \frac{\partial v(L_{j,t})}{\partial L_{j,t}}\right]}_{=0}\cdot\frac{\partial L_{j,t}}{\partial\tau_t} = 0\end{aligned} \tag{3.12.87}$$

where

$$\frac{\partial X_t}{\partial\tau_t} = \sqrt{\frac{\left[\phi q + (1-\phi)\,w\right]}{\tau_t\bar{L}_t}} \geq 0 \tag{3.12.88}$$

Then, the optimal choice of adaptation rate of a young household of belief type j is

$$\tau_t^{Yj*} = \frac{1}{\bar{L}_t}\cdot\left[\phi q + (1-\phi)\,w\right]\cdot\left(\frac{\tilde{\theta}_j\cdot\mu\gamma_{t+1}\cdot\left(p_{t+1}+\pi_{j,t}\right)}{(1+r)y_{i,t}}\right)^2 \tag{3.12.89}$$

Old Households

Old households maximize their expected utility, as given by

$$\begin{aligned} \max_{\tau_t} \mathbb{E}\left(U\left(c_{i,t},,X_t\right)\right) &= \mathbb{E}_t\left(c_{i,t}\right) + f\left(\mathbb{E}_{j,t}\left(\bar{L}_{t+1}\right)\right) \\ s.t. \quad c_{i,t} &\leq \left(1-\tau_t\right) y_t + \max\left\{p_t\left(1-\xi_{i,t}\right) L_{i,t-1} + \left(1+\hat{r}\right) S_{i,t-1}, 0\right\} \\ \tau_t &\geq 0 \end{aligned} \tag{3.12.90}$$

where $c_{i,t}$ is consumption of household i in period t and $\mathbb{E}_{j,t}$ denotes expectations formed at date t by belief type j.

Using similar steps as before, the maximization problem can be rewritten as

$$\begin{aligned} \max_{\tau_t} \mathbb{E}\left(U\left(c_{i,t+1}, X_t\right)\right) &= \left(1-\tau_t\right) y_t + (1+r) S_{i,t-1} \\ &\quad + p_{t+1}\left(1-\left(1-X_{t-1}\right)\mu\theta_{j,t}\cdot\gamma_t\right) L_{i,t-1} + f\,\mathbb{E}_{j,t}\left(\bar{L}_{t+1}\right)\right) \\ s.t. \quad \tau_t &\geq 0 \end{aligned} \tag{3.12.91}$$

and the optimal choice of adaptation rate of an old household of belief type j is given by

$$\tau_t^{Oj*} = \frac{1}{\bar{L}_t}\cdot\left[\phi q + \left(1-\phi\right) w\right]\cdot\left(\frac{\tilde{\theta}_{j,t}\cdot\mu\gamma_{t+1}\cdot\pi_{j,t}}{y_{i,t}}\right)^2 \tag{3.12.92}$$

3.12.3 Derivation of Lemma 3

The relative ordering of the adaptation rates follows directly from Assumption 1.

3.12.4 Derivation of Lemma 4

We assume that coalitions choose a adaptation rate that maximizes their joint utility function.

Coalition of Young Skeptics and Old Realists

Consider first the coalition of young skeptics and old realists. This coalition maximizes:

$$\max_{\tau_t} \mathbb{E}\left(U_{Ys,Or}\right) = \omega \cdot \left(v\left(L_{Ys,t}\right) + \mathbb{E}_t\left(c_{Ys,t+1}\right)\right) + (1-\omega) \cdot \left(\mathbb{E}_t\left(c_{Or,t}\right)\right) + f\left(\mathbb{E}_{Ys,Or,t}\left(\bar{L}_{t+1}\right)\right) \tag{3.12.93}$$

$$\begin{aligned} s.t. \quad (1-\tau_t)\, y_{Ys,t} &\leq p_t L_{Ys,t} + S_{Ys,t} \\ c_{Ys,t+1} &\leq (1-\tau_{t+1})\, y_{Ys,t+1} + \max\left\{p_{t+1}\left(1-\xi_{Ys,t+1}\right) L_{Ys,t} + (1+\hat{r})\, S_{Ys,t}, 0\right\} \\ c_{Or,t} &\leq (1-\tau_t)\, y_{Or,t} + \max\left\{p_t\left(1-\xi_{Or,t}\right) L_{Or,t-1} + (1+\hat{r})\, S_{Or,t-1}, 0\right\} \\ \tau_t &\geq 0 \end{aligned}$$

Using the no-arbitrage condition as in Lemma 2, the expectation of a young pessimists' consumption in period $t+1$, $c_{Ys,t+1}$, as formed at date t, becomes

$$\begin{aligned} \mathbb{E}_t\left(c_{Ys,t+1}\right) = (1+r)\left(\left(1-\tau_t\right) y_{Ys,t} - p_t L_{Ys,t}\right) \\ + p_{t+1}\left(1-\left(1-X_t\right)\mu \cdot \theta_{Ys,t} \cdot \gamma_{t+1}\right) L_{Ys,t} + \left(1-\tau_{t+1}\right) y_{Ys,t+1} \end{aligned} \tag{3.12.94}$$

and the expectation of an old optimists' consumption in period t, $c_{Or,t}$, as formed at date t, becomes

$$\mathbb{E}_t\left(c_{Or,t}\right) = \left(1-\tau_t\right) y_{Or,t} + (1+r) S_{Or,t-1} + p_t\left(1-\left(1-X_{t-1}\right)\mu\theta_{Or,t} \cdot \gamma_t\right) L_{Or,t-1} \tag{3.12.95}$$

Using similar definitions as in Proof of Lemma 2, the FOC for τ_t becomes

$$\begin{aligned} \omega\left(-(1+r) y_{Ys,t} + \mu\tilde{\theta}_{Ys,t} \cdot \gamma_{t+1} \cdot p_{t+1} \cdot \frac{\partial X_t}{\partial \tau_t}\right) + (1-\omega)\left(-y_{Or,t}\right) \\ + \pi_{r,s,t} \cdot \left(\omega \cdot \mu\tilde{\theta}_{s,t} \cdot \gamma_{t+1} + (1-\omega) \cdot \mu\tilde{\theta}_{r,t} \cdot \gamma_{t+1}\right) \cdot \frac{\partial X_t}{\partial \tau_t} = 0 \end{aligned} \tag{3.12.96}$$

Then, the adaptation rate preferred by a coalition of young skeptics and old realists is given by

$$\tau_t^{Ys,Or*} = \frac{1}{\bar{L}_t} \cdot \frac{1}{[\phi q + (1-\phi)\, w]} \cdot \left(\frac{\mu\gamma_{t+1} \left(\omega\tilde{\theta}_{s,t} p_{t+1} + \pi \cdot \left(\omega \cdot \tilde{\theta}_{s,t} + (1-\omega) \cdot \tilde{\theta}_{r,t} \right) \right)}{(1+\omega \cdot r)} \right)^2 \tag{3.12.97}$$

Coalition of Young and Old Skeptics

Using similar steps as above, the adaptation rate preferred by a coalition of young and old skeptics is given by

$$\tau_t^{Ys,Os*} = \frac{1}{\bar{L}_t} \cdot \frac{1}{[\phi q + (1-\phi)\, w]} \cdot \left(\frac{\tilde{\theta}_{s,t} \cdot \mu\gamma_{t+1} \left(\frac{1}{2} p_{t+1} + \pi_{s,t} \right)}{\left(1 + \frac{1}{2} r \right)} \right)^2 \tag{3.12.98}$$

Coalition of Old Realists and Old Skeptics

The adaptation rate preferred by a coalition of old realists and old skeptics is given by

$$\tau_t^{Or,Os*} = \frac{1}{\bar{L}_t} \cdot \frac{1}{[\phi q + (1-\phi)\, w]} \cdot \left(\mu\gamma_{t+1} \cdot \pi_{r,s,t} \cdot \left(\omega \cdot \tilde{\theta}_{s,t} + (1-\omega) \cdot \tilde{\theta}_{r,t} \right) \right)^2 \tag{3.12.99}$$

3.12.5 Derivation of Lemma 5

Old households maximize their expected utility, as given by

$$\begin{aligned} \max_{\tau_t} \mathbb{E}\left(U\left(c_{y,t},, \bar{L}_{t+1} \right) \right) &= \mathbb{E}_t\left(c_{y,t} \right) + f\left(\mathbb{E}_{j,t}\left(\bar{L}_{t+1} \right) \right) \qquad (3.12.100) \\ s.t. \quad c_{y,t} &\leq (1-\tau_t)\, y + \max\left\{ p_t\left(1 - \xi_{y,t} \right) L_{y,t-1} + \left(1 + \hat{r} \right) S_{y,t-1}, 0 \right\} \\ \tau_t &\geq 0 \end{aligned}$$

where $c_{y,t}$ is the consumption of an old household with income $y \in \{w, q\}$ in period t and $\mathbb{E}_{j,t}$ denotes expectations formed at date t by belief type j.

Using similar steps as in Lemma 2, the optimal choice of adaptation rate of an old

household of belief type j and with income y is given by

$$\tau_t^{Ojy*} = \frac{1}{\bar{L}_t} \cdot [\phi q + (1-\phi)\, w] \cdot \left(\frac{\mu \tilde{\theta}_{j,t} \cdot \gamma_{t+1} \cdot \pi_{j,t}}{y} \right)^2 \tag{3.12.101}$$

We determine the relative ordering of the adaptation rates preferred by the different types of old households. Specifically, as $q > w$, we have that $\tau^{OOl*} > \tau^{OOh*}$ and $\tau^{OPl} > \tau^{OPh*}$. Moreover, as $\bar{\theta} > \underline{\theta}$, we have that $\tau^{Orh*} > \tau^{Osh*}$ and $\tau^{Orl} > \tau^{Osl*}$. If it additionally holds that

$$\frac{q}{w} < \frac{\theta_{r,t}}{\theta_{s,t}} \cdot \frac{\pi_{r,t}}{\pi_{s,t}} \tag{3.12.102}$$

then, the relative ordering of the adaptation rates preferred by old households is given by

$$\tau^{Orl*} > \tau^{Orh*} > \tau^{Osl*} > \tau^{Osh*} \tag{3.12.103}$$

Otherwise, this becomes

$$\tau^{Orl*} > \tau^{Osl*} > \tau^{Orh*} > \tau^{Osh*} \tag{3.12.104}$$

3.12.6 Derivation of Lemma A1

Lemma A1. *Let there be less young than old, skeptics represent a majority ($\omega > 0.5$), and high-income households are a minority ($\phi < 0.5$). Then, if it holds that*

Assumption 2.

$$\tilde{\Theta} > \underbrace{\frac{p_{t+1} + \pi_{s,t}}{\pi_{r,t} \cdot (1+r)}}_{\textit{Assumption 1}} \cdot \underbrace{\frac{q}{\phi \cdot q + (1-\phi) \cdot w}}_{\textit{Inequality multiplier}}. \tag{3.12.105}$$

and economic inequality is sufficiently low, then we have that

$$\tau_t^{Yr*} > \tau_t^{Orl*} > \tau_t^{Orh*} > \tau_t^{Ys*} > \tau_t^{Osl*} > \tau_t^{Osh*} \tag{3.12.106}$$

and the young skeptics are pivotal. The set of feasible coalitions is then:

1. ***"High Ambition Coalition"**: Low-income, old realists ($(1-\phi)(1-\omega)$), high-income, old realists ($\phi(1-\omega)$) and young pessimists (ω), i.e. young skeptics and old realists.*

2. ***Mixed Coalition** ($2(\omega - \phi\omega) + \phi$): high-income, old realists ($\phi(1-\omega)$), young skeptics (ω), and low-income, old skeptics ($(1-\phi)\omega$). We refer to this as the "mixed coalition".*[32]

3. ***"Low Ambition Coalition"** (2ω): Young skeptics (ω), low-income, old skeptics ($(1-\phi)\omega$), and high-income, old skeptics ($\phi\omega$), i.e. young and old skeptics.*[33]

If economic inequality is sufficiently high, and it holds that

Assumption 2*.

$$\tilde{\Theta} < \frac{p_{t+1} + \pi_{s,t}}{\pi_{r,t} \cdot (1+r)} \cdot \frac{q}{\phi \cdot q + (1-\phi) \cdot w}. \tag{3.12.107}$$

then we have that

$$\tau_t^{Yr*} > \tau_t^{Orl*} > \tau_t^{Osl*} > \tau_t^{Ys*} > \tau_t^{Orh*} > \tau_t^{Osh*} \tag{3.12.108}$$

and, the young skeptics are again pivotal. The set of feasible coalitions is then:

1. ***"High Ambition Coalition*"** ($1 - \phi + \omega$): low-income, old realists ($(1-\phi)(1-\omega)$), young skeptics (ω), and low-income, old skeptics ($\omega(1-\phi)$), i.e. young skeptics and low-income old.*

[32] For $\omega > 0.5$, a mixed coalition is always larger - and thus politically more powerful than the high ambition coalition. Moreover, under Assumption 1, a mixed coalition is always politically more powerful than the low-ambition coalition.

[33] If $\omega > 0.5$, the low-ambition coalition is always politically more powerful than the high ambition coalition. Hence, the high ambition coalition always has the least political power.

2. ***Mixed Coalition**** *($2(\omega - \phi\omega) + \phi$): high-income, old realists ($\phi(1-\omega)$), young skeptics (ω), and low-income, old skeptics ($(1-\phi)\omega$) households. We refer to this as the "mixed coalition".*[34]

3. ***"Low Ambition Coalition*"** *($\omega\phi$): Young skeptics (ω), high-income, old realists ($(1-\omega)\phi$), and high-income, old skeptics ($\phi\omega$), i.e. young skeptics and high-income, old.*

If Assumption 2 is not satisfied (in either case), the high-income, old realists emerge as pivotal group and the political equilibrium is characterized by the prevailing of the mixed coalition.
The adaptation rates that maximize joint utility of each coalition when economic inequality is sufficiently low are:

1.

$$\tau_t^{Ys,Orh,Orl*} = A \cdot \left(\frac{\omega \tilde{\theta}_{s,t} p_{t+1} + \left(\omega \cdot \tilde{\theta}_{s,t} + (1-\omega) \cdot \tilde{\theta}_{r,t}\right) \cdot \pi_{r,s,t}}{(1+\omega r)} \right)^2,$$

2.

$$\tau_t^{Ys,Orh,Osl*} = A \cdot \left[\phi q + (1-\phi)\, w\right]^2 \cdot \left(\frac{\omega \cdot \tilde{\theta}_{s,t} p_{t+1} + \left(\omega(2-\phi) \cdot \tilde{\theta}_{s,t} + (1-\omega)\phi \cdot \tilde{\theta}_{r,t}\right) \cdot \pi_{r,s,t}}{\omega \cdot (1+r) \cdot \left[\phi q + (1-\phi)\, w\right] + (1-\omega)\phi \cdot q + \omega(1-\phi) \cdot w} \right)^2,$$

3.

$$\tau_t^{Ys,Osh,Osl*} = A \cdot \left(\frac{\tilde{\theta}_{s,t} \cdot \frac{1}{2} p_{t+1} + \pi_{s,t}}{\left(1 + \frac{1}{2} r\right)} \right)^2.$$

and the adaptation rates that maximize joint utility of each coalition when economic inequality is sufficiently high are:

1.

$$\tau_t^{Ys,Orl,Osl*} = A \cdot \left[\phi q + (1-\phi)\, w\right]^2 \cdot \left(\frac{\omega \cdot \tilde{\theta}_{s,t} p_{t+1} + \left(\omega(2-\phi) \cdot \tilde{\theta}_{s,t} + (1-\omega)(1-\phi) \cdot \tilde{\theta}_{r,t}\right) \cdot \pi_{s,r,t}}{\omega\,(1+r)\,\left[\phi q + (1-\phi)\, w\right] + (1-\phi)\, w} \right)^2,$$

[34] If $\phi < \omega$, the high ambition coalition is always larger and thus politically more powerful than a mixed coalition.

2.

$$\tau_t^{Ys,Orh,Osl*} = A \cdot [\phi q + (1-\phi)\, w]^2 \cdot \left(\frac{\omega \cdot \tilde{\theta}_{s,t} p_{t+1} + \left(\omega(2-\phi) \cdot \tilde{\theta}_{s,t} + (1-\omega)\phi \cdot \tilde{\theta}_{r,t}\right) \cdot \pi_{s,r,t}}{\omega \cdot (1+r) \cdot [\phi q + (1-\phi)\, w] + (1-\omega)\phi \cdot q + \omega(1-\phi) \cdot w} \right)^2,$$

3.

$$\tau_t^{Ys,Orh,Osh*} = A \cdot [\phi q + (1-\phi)\, w]^2 \cdot \left(\frac{\omega \cdot \tilde{\theta}_{s,t} p_{t+1} + \left(\omega(1+\phi)\tilde{\theta}_{s,t} + (1-\omega)\phi \cdot \tilde{\theta}_{r,t}\right) \cdot \pi_{s,r,t}}{\omega\,(1+r)\,[\phi q + (1-\phi)\, w] + \phi q} \right)^2.$$

Alternatively, if Assumption 2 is not satisfied (in either case), the adaptation rate that maximizes the joint utility of the prevailing coalition is given by $\tau_t^{Ys,Orh,Osl*}$.

3.13 Additional Simulations: Extended Model

3.13.1 Gradually Increasing Inequality

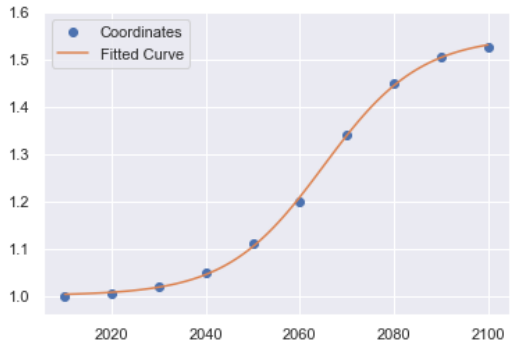

Figure 3.13.9: **The evolution of the inequality multiplier following a fitted S-curve in the extended model**.

3.13.2 Escalating Inequality

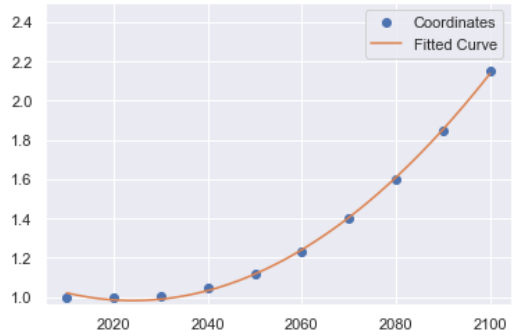

Figure 3.13.10: **The evolution of the inequality multiplier following a convex curve in the extended model.**.

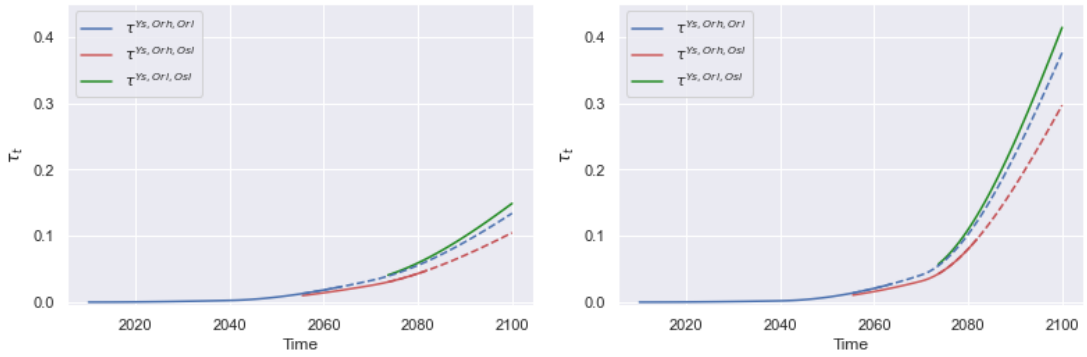

Figure 3.13.11: **Tipping of the adaptation rate**

Key: The time path for the adaptation rate when the political equilibrium tips around 2050, and 2080, under SSP1-2.6 (left panel), and SSP3-7.0 (right panel), when inequality rises at an increasing rate.

Chapter 4

Funding the Fittest? Pricing Climate Transition Risk in the Corporate Bond Market[1]

Abstract

This chapter studies whether climate transition risk affects the cost of capital and how investors value green innovation. Using confidential bond-level holdings and global firm data, we find evidence of a positive transition risk premium. This premium is significantly lower for emission-intensive firms that engage in green innovation, indicating that investors recognize and reward efforts to transition to greener technologies. We show that institutional investors, particularly mutual funds, have a relatively higher demand for bonds issued by transitioning firms. Their holdings influence the extent to which environmental performance is reflected in yield spreads. Our findings suggest that risk pricing is the primary channel through which environmental performance influences bond yield spreads. This underscores the importance of investors with greater risk-bearing capacity in directing capital toward firms most essential to the green transition.

Keywords: Climate Transition Risk, Carbon Premium, Green Innovation, Bond Markets, Institutional Investors.

JEL codes: G12, G23, Q51.

[1] This chapter is based on Boermans, M., Bun, M., & Van der Straten, Y. (2024). Funding the fittest? Pricing of climate transition risk in the corporate bond market. DNB Working Paper No. 797. The views expressed are those of the authors and do not necessarily reflect official positions of De Nederlandsche Bank nor the Eurosystem. Data have been cleared by the Eurosystem for non-disclosure of confidential data. Details are available at www.ecb.europa.eu/stats/financial_markets_and_interest_rates/securities_holdings/html/index.en.html.

4.1 Introduction

The transition to net-zero emissions by 2050 involves significant uncertainties, particularly as delays in climate action increase the risk of a disorderly transition. This exposes firms – especially those with high emissions – to regulatory, technological, and legal challenges that may undermine their financial performance and expose its investors to downside risks. Anticipating such risks, forward-looking investors may reallocate capital across firms, adjusting their cost of capital in ways that can either accelerate or hinder the green transition. As such, since the adoption of the Paris Agreement in December 2015, sustainable investing has gained prominence. Yet, reallocating capital away from high-emitting firms toward already low-emitting firms may be counterproductive, as the marginal climate impact of investing in already green firms is limited (Hartzmark and Shue, 2023). Moreover, firms that are currently brown may play a critical role in advancing green technologies (Cohen, Gurun, and Nguyen, 2023). This raises the question whether investors are channeling capital toward firms most essential to the transition – those that are currently emission intensive but actively invest in cleaner technologies.

This paper examines how corporate bond investors price climate transition risk and whether they recognize firm-level efforts to reduce future exposure through green innovation. Specifically, we explore (i) whether investors value green innovation in the presence of transition risk and (ii) which types of investors hold more bonds issued by emission-intensive yet green-innovative firms – which we refer to as "transitioning firms". We focus on corporate bonds given their central role in firm financing, serving as the marginal source of capital for many companies globally (Gourio, 2013). This is especially true for emission-intensive firms, which often depend heavily on bond issuance to fund their operations (Papoutsi, Piazzesi, and Schneider, 2022). Moreover, unlike equity investors, who can benefit from upside potential, bond investors are primarily concerned with downside risks that threaten a firm's ability to meet debt obligations. Since climate risk predominantly represent downside risk, their pricing in cor-

porate bond markets is especially relevant (Ilhan, Sautner, and Vilkov, 2021; Hoepner, Oikonomou, Sautner, Starks, and Zhou, 2024).

We document three main findings. First, we provide evidence that corporate bond investors price climate transition risk, as bond yield spreads rise in a firm's emission intensity. Importantly, we show that this premium is smaller for firms that make the effort to transition to greener technologies, suggesting that investors perceive green innovation as reducing technological uncertainty surrounding the green transition. Second, we find that European institutional investors, and mutual funds in particular, have a relatively higher demand for bonds issued by transitioning firms. Third, our results suggest that risk pricing is the primary channel through which environmental performance influences bond yield spreads, consistent with a default risk channel whereby green innovation reduces firms' vulnerability to transition risks. These findings underscore the importance of investors with greater risk-bearing capacity in supporting the green transition by providing lower-cost financing to brown firms investing in greener technologies.

We obtain these findings by combining global firm-level data on greenhouse gas emissions from Trucost Environmental with confidential bond-level holdings data from the European Central Bank (ECB). Our data on bond holdings is sourced from the ECB Securities Holdings Statistics Sectoral, which provides detailed security-level information on aggregate portfolio holdings by financial and non-financial investors across all European countries for bonds issued worldwide. This dataset covers bond holdings by insurance companies, pension funds, mutual funds, banks, other financial institutions, non-financial corporations, governments, and households. Our sample represents approximately 58 percent of all reported security holdings by European investors in stock-listed, non-financial corporate issuers worldwide.

We consider emission intensity as our measure of a firm's environmental performance. While absolute emissions are important for assessing a firm's total environmental footprint, emission intensity is more informative for bond investors because the financial impact of climate-related costs depends on a firm's financial ability to absorb

those costs. As emission intensity measures these costs relative to a firms revenue, this metric is particularly relevant for corporate bond investors. While reducing future emissions is central to the green transition, conventional emissions data – which capture firms' past and present carbon emissions –provides a limited view of firms' forward-looking efforts to transition to greener technologies. For instance, Cohen et al. (2023) find that brown firms are often key innovators in green technologies. These firms tend to develop a significantly higher amount of green patents, which are also more often technologically successful. We therefore incorporate a measures of green innovation alongside carbon emissions in our bond pricing analysis. We enhance our dataset with firm-level data on (green) patents from Orbis Intellectual Property to assess how investors value firms' efforts to transition to greener technologies. We collect data on the total number of patents per company and identify those classified as green patents under the Climate Change Mitigation and Adaptation category of the Cooperative Patent Classification (CPC) (Haščič and Migotto, 2015). Our dataset includes nearly 20 million patents, of which approximately 1-2 percent are classified as green patents. To account for differences in firms' overall patenting activity, we measure green innovation as the share of green patents relative to a firm's total patents (Bolton, Kacperczyk, and Wiedemann, 2023; Cohen et al., 2023; Li, Shan, Tang, and Yao, 2024).

We adopt a corporate perspective and focus on within-firm variation over time to measure the effect of changes in a firm's emission intensity and green innovation on its financing costs. To this end, we control for a rich set of firm and bond characteristics, as well as firm fixed effects and industry-time fixed effects. This approach allows us to account for unobserved, persistent firm characteristics and industry-wide time varying shocks, thereby isolating the impact of changes in firms' environmental performance on bond pricing. Our regression analysis, covering the period from 2016-Q1 to 2021-Q4, provides evidence of a positive carbon premium that increases with a company's emission intensity. Importantly, we find that emission-intensive firms with a higher share of green patents face significantly lower bond yield spreads. In other words, the carbon premium is lower for firms actively engaging in green innovation compared to their

non-(green-)innovative peers. A one standard deviation increase in the green patent ratio reduces the carbon premium by approximately 15 percent. This suggests that investors recognize and reward the efforts emission-intensive firms make to transition to greener technologies.

We confirm that this result holds across a range of robustness tests. First, we consider alternative measures of green innovation. Our findings remain robust when using a stricter classification of green patents, focusing on those aimed at reducing greenhouse gas emissions from energy generation, transmission, or distribution (Acemoglu, Aghion, Barrage, and Hémous, 2023). The results become stronger when we focus on "blockbuster" green patents – those among the top five percent most cited within their CPC class. Generally, we find that the combined effect of emission intensity and green patenting becomes more pronounced when green patents are technologically more relevant, as measured by their forward citations. We further verify that our results are not driven by general investment, R&D expenditures, or patenting activity. Instead, we show that it is specifically green innovation that matters for investors. We also verify that our results hold when excluding firms in the utilities sector, which, although highly emission-intensive, also innovate extensively in green technologies.

Since the Corporate Sector Purchase Programme (CSPP) of the ECB has significantly eased financing conditions in the euro area corporate debt market, we further verify that our results are not driven by bond eligibility for purchase under the CSPP, nor by actual purchases made by the ECB. The CSPP, which started in June 2016, involved purchases of corporate sector bonds by the Eurosystem. To ensure our results are not influenced by the CSPP, we account for bond eligibility and actual purchases made by the ECB. While bonds eligible for purchase under CSPP exhibited lower yield spreads, we show that it did not disproportionately favor emission-intensive companies that also innovate in the green space. Furthermore, as there is some evidence that banks are reducing lending to emission-intensive firms due to climate risks (e.g., Ivanov, Kruttli, and Watugala, 2024; Degryse, Goncharenko, Theunisz, and Vadasz, 2023), we also ensure that our results are not driven by a disproportionate expansion in bond supply

from these transitioning firms.

Our findings suggest that investors fund firms are "fit" for the green transition – rewarding those that are currently emission intensive but actively investing in greener technologies. To better understand the implications of this finding, we explore the impact of green innovation on firm's future emissions. Overall, our results do not provide a definitive answer as to whether green innovation directly improves environmental performance, which aligns with the findings of Bolton et al. (2023). This raises the question why investors factor green innovation into the bond pricing relationship. One possible interpretation is that investors value the option value embedded in green patents: the ownership of such patents may signal technological readiness or resilience in adapting to adapt to evolving technological conditions associated with the transition. This interpretation is consistent with investors viewing green innovation as a signal of reduced technological uncertainty and thereby lower transition risk.

We investigate which European investors are more inclined to incorporate climate transition risk into their investment decisions. Specifically, we explore which investor types are more likely to demand bonds issued by emission-intensive firms that engage in green innovation. To elicit investor demand, we follow the methodology of Khwaja and Mian (2008) and Acharya, Banerjee, Crosignani, Eisert, and Spigt (2024). More precisely, we compare the demand of different investor types for bonds issued by firms with a similar exposure to climate transition risk, controlling for potential differential portfolio choices of investors types over time and for all other potential time-varying firm characteristics that might interact with the portfolio choice (Acharya et al., 2024). We focus specifically on the role of institutional investors and banks. Our results demonstrate that European institutional investors, and mutual funds in particular, have a higher demand for bonds issued by transitioning firms.[2] This suggests that mutual funds are more willing to finance brown firms that are investing in green technologies.

[2] While we only observe the holdings of European investors, these results may be geographically generalizable. Edmans, Gosling, and Jenter (2024) find few geographic differences in views on ES in a global survey of funds marketed in the US, EU, UK, and elsewhere. Therefore, European investors do not seem to behave differently from those in other regions.

We also assess whether differences in demand across investor types have pricing implications. We examine whether the sensitivity of bond yields to firms' environmental performance differs depending on the volume of holdings of a given investors type. We measure the holdings of specific investors relative to the total outstanding amount for a given bond and period, accounting for the relative size of each investor sector (Crosignani, Faria-e Castro, and Fonseca, 2020). Consistent with our demand estimation, we find that the holdings of European institutional investors influence the extent to which environmental performance is reflected in bond yield spread. European mutual funds play a crucial role in this effort, lowering the cost of capital for transitioning firms, relative to other emission-intensive firms.

Given the substantial increase in flows to European sustainable funds over our sample period, these findings raises the question whether the demand from mutual funds primarily reflects a green preference or is consistent with risk-based pricing. Consistent with a default risk channel (Carbone, Giuzio, Kapadia, Krämer, Nyholm, and Vozian, 2021; Seltzer, Starks, and Zhu, 2022), we find that the pricing effects are concentrated in the segment of firms which are closer to financial distress. To evaluate the role of exposure to climate risk more specifically, we construct a market-based measure of a firm's climate risk exposure. Specifically, we estimate a firm's exposure to aggregate climate risk and examine whether the effect of environmental performance on bond yield spreads is more pronounced for firms with a higher climate risk exposure. We use innovations in the Climate Change News Index developed by Engle, Giglio, Kelly, Lee, and Stroebel (2020) as a proxy for aggregate climate risk. This index measures the unexpected component of climate change-related news intensity in newspapers, allowing us to capture exogenous changes in climate-related concerns.

We leverage data on stock holdings by financial and non-financial investors across European countries for firms worldwide, which allows us to obtain firm-level stock returns. We estimate each firm's stock return sensitivity to aggregate climate risk, which we refer to as the firm's "Climate Beta". We assess whether the effect of the environmental performance on bond yields is more pronounced for firms with a greater

exposure to aggregate climate risk, as measured by their Climate Beta. Our findings indicates that the carbon premium is higher for firms that have a larger exposure to climate risk. At the same time, the reduction in the carbon premium due to green innovation is higher for firms with larger exposure to climate risks. In other words, for firms that are more vulnerable to climate risk, investors place greater value on efforts to transition, as measured by their green patenting activity.

Our evidence suggests that risk pricing is as the primary channel through which environmental performance influences bond yield spreads. This highlights the importance of investors with risk-bearing capacity in reallocating capital toward firms that are currently emission-intensive but are actively investing in cleaner technologies. More broadly, our results underscore the importance of incorporating climate risk into credit assessments and investment decisions more dynamically. As climate risks become more financially relevant, this can increase firms' incentives to invest in green innovation and facilitate the transition to a low-carbon economy.

4.1.1 Related literature

This paper relates to two broad strands of literature. First, our paper contributes to the literature on the pricing of climate transition risk in financial markets. This literature has focused predominately on stock markets. Bolton and Kacperczyk (2021) find evidence of a positive carbon premium in the cross-section of U.S. stock returns and Bolton and Kacperczyk (2023) show that this premium is observed in global stock markets. Hsu, Li, and Tsou (2022) consider the asset pricing implications of industrial pollutants, rather than just CO2-related emissions, and show that environmental policy uncertainty helps price the cross-section of stocks returns. Aswani, Raghunandan, and Rajgopal (2024) and Zhang (2024) suggest that the association between corporate emissions and stock returns disappears when using emission intensity rather than unscaled emission levels. Boermans and Galema (2023) confirm this result for European stock, but find a carbon premium for non-European stocks using emission intensity. Pástor, Stambaugh, and Taylor (2022) and Ardia, Bluteau, Boudt, and Inghelbrecht (2023)

empirically test whether green firms outperform brown firms when concerns about climate change increase unexpectedly using ESG scores (Pástor, Stambaugh, and Taylor, 2021).[3] Eskildsen, Ibert, Jensen, and Pedersen (2024) conduct a replication study and propose a new measure of environmental performance, combining information on firms absolute emissions, their emission intensities, and their E(SG) scores. They find evidence of a small, yet significant carbon premium, which is higher in greener countries and rises over time. Li et al. (2024) further show using a text-based measure of transition risk that firms facing high transition risk have been valued at a discount in recent years.

A more recent literature studies whether climate transition risk is accounted for in bank lending decisions (e.g., Sastry, Verner, and Marques-Ibanez, 2024; Ivanov et al., 2024; Altavilla, Boucinha, Pagano, and Polo, 2023; Kacperczyk and Peydró, 2022; Delis, Greiff, Iosifidi, and Ongena, 2024). Using syndicated loan data, D'Arcangelo, Kruse, Pisu, and Tomasi (2023) show that that the cost of capital is lower for firms with lower emission intensity, especially in countries where climate-change mitigation policies become more stringent (e.g., Ali, Nadeem, Pandey, and Bhabra, 2023; Heinkel, Kraus, and Zechner, 2001). Using administrative credit registry data from Europe, Altavilla et al. (2023) provide evidence that loan spreads are higher for emission-intensive firms. This effect is particularly driven by banks that publicly commit to environmentally responsible lending practices. Sastry et al. (2024), however, highlight the limits of voluntary commitments for decarbonization, finding that net zero banks neither reduce credit supply to sectors targeted for decarbonization, nor reduce financed emissions through engagement. Also Giannetti, Jasova, Loumioti, and Mendicino (2023) show that banks that emphasize climate change in their disclosures do not adhere to more environmentally friendly lending practices, as these banks continue their relationships with existing brown borrowers, especially with those that exhibit financial underperformance.

Some research has also been conducted on the pricing of climate transition risk in

[3] Bauer, Huber, Rudebusch, and Wilms (2022) find more generally and for a range of methodologies that green stocks provide higher returns than brown stocks for much of the past decade. Also Loyson, Luijendijk, and Wijnbergen (2023) do not find evidence that carbon risk is being priced in the European equity market.

the corporate bond market.[4] Duan, Li, and Wen (2023), who focus on bonds issued by U.S. companies and traded on the U.S. public market, find that bonds of more carbon-intensive firms earn significantly lower returns due to investor underreaction to the predictability of emission intensity for firm's financial performance. In contrast, Seltzer et al. (2022) provide evidence that climate regulatory risks affect bond yield spreads and bond ratings, exploiting the Paris Agreement as a shock to climate regulation.[5] We contribute to the literature by considering the forward-looking efforts firms undertake to transition to greener technologies in our bond pricing analysis. Our findings indicate that the 'carbon premium is smaller for emission-intensive companies that engage in green innovation, indicating that investors value firm's efforts to transition to greener technologies. Additionally, our detailed bond holdings data allows us to uniquely identify investors demand for bonds of firms with varying environmental profiles. That is, our data uniquely allows us to compare the demand of different investor types for bonds issued by firms with a similar exposure to climate transition risk, controlling for potential differential portfolio choices of investors in different holder areas and sectors over time and for all other potential time-varying firm characteristics that might interact with the portfolio choice (Acharya et al., 2024). We show that institutional investors, and particularly mutual funds, have a relatively higher demand for bonds issued by transitioning firms. Their holdings influences the extent to which environmental performance is reflected into yield spreads, lowering the cost financing to firms that, despite being emission-intensive today, are actively investing in greener technologies to mitigate climate change.

Second, this paper also relates to the literature on green innovation and financial performance.[6] Battiston, Monasterolo, and Montone (2023); Leippold and Yu (2023) fo-

[4] While we focus on the corporate bond market as a whole and do not focus on corporate green bonds exclusively, our paper also relates to studies in this literature (e.g., Flammer, 2021; Pietsch and Salakhova, 2022; Zerbib, 2019; ElBannan and Löffler, 2024)).

[5] Broeders, de Jonge, and Rijsbergen (2024) also find evidence of a carbon premium that investors demand for bonds issued by firms with high emissions in the euro area.

[6] Our paper somewhat relates to the literature on the real effect of climate risk pricing and green innovation (see e.g., Hartzmark and Shue, 2023; Dugoua and Gerarden, 2023; Leippold and Yu, 2023; ElBannan and Löffler, 2024; Bolton et al., 2023; Cohen et al., 2023).

cus on the association between green innovation and stock returns. Leippold and Yu (2023) develop a text-based green innovation using earnings-call reports and show that stocks of firms with higher green innovation measures have lower expected returns. Battiston et al. (2023) find that the adoption of sustainable technologies is associated with better future financial and operating performance in the long run. Considering credit supply, Accetturo, Barboni, Cascarano, Garcia-Appendini, and Tomasi (2022) show for Italian SMEs that there is a large positive elasticity of green investments to credit supply. Instead, Hartzmark and Shue (2023) question the effectiveness of capital reallocation based solely on firms' current emission profiles. Specifically, the authors argue that directing capital away from brown firms and toward green firms may be counterproductive as it makes brown firms more brown without making green firms more green. We contribute to this literature by showing that corporate bond investors do not reward green innovation in isolation. Rather, they value green innovation specifically when it is undertaken by firms that are currently among the highest emitters. This indicates that sustainable investing – when directed toward transitioning firms – can play a meaningful role in supporting emissions reductions where they are most needed.

4.2 Data

We construct a comprehensive dataset by compiling data from various sources. Our sample covers the period 2016-Q1 up until 2021-Q4. The data is reported at quarterly frequency at the security-by-security level for bonds issued worldwide. We use confidential data on security-level portfolio holdings from the ECB Securities Holdings Statistics Sectoral (SHS-S, hereafter referred to as SHS). This data is complemented with the ECB Centralised Securities Database (CSDB), which provides various issuer- and bond characteristics at the security level.[7] We use Trucost Environmental for data on corporate carbon emissions and collect (green) patent information from Orbis Intellectual Property (IP). Corporate fundamentals and bond characteristics are obtained from

[7] Securities are identified by unique security codes, most commonly using ISIN codes, which we use to match the holdings data with the firm-level data.

Table 4.2.1: Summary statistics

	Mean	Median	SD	P10	P90
Environmental Variables					
(Scope1 + Scope2) Emission Intensity	2.791	0.494	4.914	0.117	8.958
(Scope1 + Scope2) Absolute Emissions (in log)	14.669	14.236	2.107	12.242	17.431
Green Patent Ratio	0.007	0.001	0.021	0.001	0.017
Bond Characteristics					
Yield to Maturity (%)	2.119	1.786	2.255	-0.006	4.375
Spread (%)	1.426	0.962	2.003	0.287	3.021
Bond Holding Value (in m EUR)	201.965	55.799	304.004	2.952	630.624
Amount Outstanding (in m EUR)	658.170	500	539.658	107.004	1293.103
Fixed Coupon	0.901	1	0.299	1	1
EUR	0.348	0	0.476	0	1
USD	0.503	1	0.500	0	1
Green bond	0.012	0	0.112	0	0
Corporate Fundamentals					
Revenue (in bn EUR)	57.264	29.117	83.841	4.899	148
Total Assets (in bn EUR)	91.157	53.262	93.731	8.788	277
Total Debt (in bn EUR)	28.917	16.606	32.030	2.374	67.456
Profitability-Ratio (%)	5.032	4.039	5.830	-0.284	11.953
Leverage-Ratio (%)	32.442	30.629	12.947	17.942	50.677
Cash-Ratio (%)	5.504	3.320	8.165	0.323	9.557
Investment-Ratio (%)	12.519	7.397	14.528	1.160	33.469

Note: Based on 38,374 observations, reported at quarterly frequency and the security-by-security level. Absolute emissions levels are measured in CO2e and are reported in natural logarithms. Emission intensity, measured in CO2e/USDm, is scaled by a factor 1/100 and winsorized at the 2.5 percent level. Yield to maturity is winsorized at the 99th percentile. Fixed coupon is a dummy which is equal to 1 if a bond has a fixed coupon. EUR respectively USD are dummy variables, which are equal to 1 if a bond is denominated in euros respectively dollars. Green bond is a dummy which is equal to 1 if a bond has a green bond label. The profitability-ratio is defined as net income dividend by total assets (ROA). Leverage is defined as total debt divided by total assets. The cash- and investment ratio are defined as cash and capital expenditures divided by total assets, respectively. All ratio's are reported in percentages.

Refinitiv. Table 4.2.1 provides summary statistics.[8]

4.2.1 Security-level portfolio holdings

The Securities Holdings Statistics provides detailed information on aggregate security-level portfolio holdings by financial and non-financial holders from all 20 euro area countries (denoted by c), as well as six other European Union countries not part of the euro area. SHS is operated by the European System of Central Banks (ESCB) and data is collected by national statistics offices of the ECB itself. The data is reported

[8] The European firms in our sample are significantly larger than most European firms. We verify that other firm characteristics, such as leverage, cash-ratio and the profitability ratio, are comparable to those of the segment of (very) large European firms in Amadeus. The European firms in our sample account for 1-1.5 billion ton of CO2 emissions annually, which constitutes approximately 60 percent of the overall emissions in the European Union as reported by Trucost.

quarterly at the security-by-security level for bonds issued globally.[9] In each period, we observe the bond holdings value held by a specific holder (j), which is identified at the country-sector level for each period t. Investors are classified into 8 distinct investor sectors (denoted by s). Specifically, we observe the bond holdings of banks, insurance companies, pension funds, mutual funds (including money market funds and other investment funds), other financial institutions (including securitizations vehicles), non-financial corporations, governments and households (including non-profit institutions serving households). From the SHS data, we thus observe how much of each unique security each sector in a given European country holds. The magnitude of holdings (as measured by total bond holdings at market value) within our sample encompasses 1 trillion euro in 2016-Q1 and rises to 1.46 trillion euro (in 2021-Q4), which covers approximately 58 percent of all security holdings reported by euro area investors for stock-listed, non-financial corporate issuers worldwide.[10]

The CSDB complements the European holdings data with various issuer - and bond characteristics at the security level. The CSDB provides data on the issuer name and the country of issuance. It also contains a time series of the yield to maturity and the amount of the debt that is outstanding in a given quarter. The yield to maturity is reported at the end of the quarter.[11] [12] Since we are interested in estimating risk premia, we determine the return in excess of the risk free rate by subtracting the maturity-matched eurozone central government bond par yield curve spot rate from the yield to maturity.[13] We also source data on bond credit ratings from the CSDB. Ratings are reported at the end of the quarter, by ratings agencies Fitch, Moody's, an S&P to the

[9] We focus on positions, which are reported at market value. Nominal values are also available, which are given the aggregated nominal amount of the security, excluding accrued interest.

[10] Short-positions, non-active securities, and investments in tax havens are excluded. Small positions, highly implausible prices, and debt types as warrants and equity like debt are dropped as well.

[11] To reduce the impact of outliers, we winsorize the yield to maturity at the 99th percentile.

[12] Since bonds are frequently observed for multiple periods, we assess the time series properties of bond yields by estimating an autoregressive model in Appendix A1.A, which confirms that bond yields are stationary. We also plot the evolution of the mean and median bond yields over time in Figure 4.6.2 in Appendix A1.A.

[13] The percentage of bonds within our sample which are denominated in euros is 34.8 percent. Since a large amount of bonds within our sample is denominated in US dollars (50.3 percent), we use Treasury Rates when determining the spread for these bonds. Bonds denominated in other currencies are benchmarked against the euro area rates.

ECB.[14]

We also obtain information on the coupon rate, the currency in which the bond is denominated, and the residual maturity of our bonds. To take into account a bond's residual maturity in our regressions, we construct a dummy variable which indicates whether the residual maturity of the bond is longer than 10 years. Within our sample, approximately 21 percent of bonds have a residual maturity longer than 10 years, and the average maturity of bonds is approximately 9 years. The CSDB also contains information on green bond labels. From the 3,348 bonds within our sample, 73 bonds have a green bond label and these are issued by 37 distinct companies.

4.2.2 Corporate environmental performance

We collect information on corporate carbon emissions from Trucost Environmental, which provides firm-level data on carbon and other greenhouse gas emissions annually. Trucost's global coverage significantly expands after 2016, coinciding with the Paris Agreement, which raised climate change awareness and emphasized the importance of measuring and reporting environmental data (Bolton and Kacperczyk, 2021).[15] As the data is published with a considerable publication lag, our analysis focuses on the period from 2016-Q1 until 2021-Q4. Trucost provides data on absolute carbon emissions (measured in tons of CO2e) and emission intensities, which are given a company's emissions relative to its revenue, measured in tons of CO2 emissions per million dollars of revenue (CO2e/USDm). A distinction is made between three sources of emissions. Scope 1 emissions cover emissions from the use of fossil fuels in the companies' production (direct emissions). Scope 2 emissions cover indirect emissions, which stem from the purchase and consumption of heat, steam and electricity by a company. Scope 3

[14] Ratings data is only available for 16,914 observations, which is 43 percent of our main sample. Bond credit ratings range from 1 to 22. A bond rating of 1 corresponds to an AAA-rating, while a bond rating of 22 corresponds to a D-rating. Within our main sample, the average credit rating is 7.350 (standard deviation of 2.530), which corresponds to an upper medium-grade (A-) bond. We take the average of ratings across the three rating providers and group credit ratings into 7 rating classes, where bonds with an AAA rating fall in category 1 and bonds with a C/D rating fall in category 6.

[15] Trucost reports emissions data for both public and private companies, our study is limited to public companies for which we have bond data available.

emissions cover indirect emissions, which are are the result of activities from assets not owned or controlled by the company, but that arise along its value chain. These emissions are more challenging to measure and are less frequently reported, often requiring estimates from data providers. Due to the lack of methodological clarity in estimating Scope 3 emissions, the data are often noisy and inconsistent compared to Scope 1 and 2 emissions (Klaaßen and Stoll, 2021). Therefore, we exclude Scope 3 emissions from our analysis.

We construct a measure of a company's environmental performance by jointly considering Scope 1 and Scope 2 emissions. Firms with higher emissions are subject to greater regulatory and operational costs as they adjust to stricter environmental policies. While absolute emissions are important for assessing a firm's total environmental impact, emission intensity – which measures these costs relative to a company's revenue – is more informative for bond investors because the financial impact of climate-related costs depends on a firm's financial ability to absorb those costs. Firm with high absolute emissions but strong revenue generation may be better positioned to absorb climate-related costs than a firm with lower emissions but also weaker financials. Emission intensity captures these costs relative to a firms financial capacity, measuring the effect on its creditworthiness. Since this is particularly relevant for corporate bond investors, we measure a company's emissions relative to its revenue in the same year[16]:

$$\text{Emission Intensity}_{f,t} = \frac{\text{Scope 1}_{f,t} + \text{Scope 2}_{f,t}}{Revenue_{f,t}}$$

where emission intensity is reported in tons of CO2e/USDm.[17] [18] We plot the evolution of mean (median) emission intensity at the firm-year level in Figure 4.6.3 in Appendix

[16] We test the robustness of our main results by considering absolute emissions instead of emission intensity in Appendix A4.F. We also find that our results hold when using absolute emissions as an explanatory variable instead of emission intensity.

[17] We scale 'Emission Intensity' by a factor 1/100 for exposition, and winsorize it at the 2.5 percent level to reduce the impact of outliers (Bolton and Kacperczyk, 2021).

[18] Our measure is similar to the ECB Climate Indicators for the financial sector's carbon intensity and the financed emissions when measuring carbon emissions in absolute terms, (see European Central Bank, 2024) and used in others studies (e.g., Andersson, Bolton, and Samama, 2016; Boermans and Galema, 2023; Aswani et al., 2024).

A1.B, which shows that, on average, emission intensity falls by 5 percent annually over our sample period.[19] In our analysis, we study whether this decline is partly explained by green innovation by emission-intensive firms.

4.2.3 (Green) patent information

We obtain data on (green) patents from Orbis IP, which provides comprehensive patent information for public and private companies filed with various patent offices globally, including the European Patent Office (EPO), the US Patent Office (USPTO), and the Japanese Patent Office (JPO). We match the security identifiers in our primary sample with their corresponding identifiers in Orbis (Bureau Van Dijk-ID numbers) to track all patent filings registered by a given company within our sample. We identify a total of 19.4 million patent filings associated with 1,240 unique companies, which is approximately 84 percent of all firms on which we obtain information in SHS, Trucost and Refinitiv.[20] We obtain information on the patent publication number, the priority - and application date, the identity of the current owners, the description of the patent, the classification according to its CPC-code, and the forward citations of each patent. Patents are assigned to each of their respective owners, and we use the priority date—the first filing date of a patent application—to assign each patent to the appropriate year.[21]

Since we are interested in green innovation, we utilize Cooperative Patent Classification (CPC) codes to identify companies' green patents. We follow Haščič and Migotto (2015) and consider patents in the class on Climate Change Mitigation and Adaptation

[19] We also assess the time series properties of our emission intensity variable (see Appendix A1.B). Our estimates show considerable persistence. Once controlling for time- and firm specific effects, however, there is no evidence of a unit root.

[20] Following Hémous, Olsen, Zanella, and Dechezleprêtre (2025), we include applications and not-granted patents. Certain patent office may only formally grant a patent if the applicant requests an examination of the invention. However, this may only be requested once their legal rights are challenged.

[21] The priority date is used to determine the novelty of the invention and is crucial for patent procedures, since it marks the date from which legal rights associated with the patent can be claimed. For statistical purposes, the priority date is considered the closest approximation to the date of invention Haščič and Migotto (2015). If the priority date is unavailable, we substitute it with the application date. Generally, we verify that our main results continue to hold when using the application date (rather than the priority date) to assign the invention to a given year in Table 4.9.25 in Appendix A4.E.

Table 4.2.2: Number of Patents and Green Patents Filed over the Sample Period

Variable	2016	2017	2018	2019	2020	2021
Patents^a	641,047	650,080	648,820	627,067	565,062	476,300
Patents^g	558,027	568,524	567,110	548,989	494,080	416,317
Green Patents	7,661	8,235	8,695	8,714	6,717	9,804

Note: Patents^a represents the number of patents filed by all companies in our sample. Patents^g refers to the number of patents (green, brown, and other) filed by companies that have at least one green patent in our sample. Green patents indicates the number of green patents filed by companies within our sample.

(with CPC-code Y02) as green patents.[22] This process results in about 240,000 green patent filings by 400 unique companies. Hence, green patents represent only 1.2 percent of the total number of patent filings within our dataset and among the companies in our sample engaged in patenting, only 32 percent also file green patents. However, these companies are collectively responsible for 90 percent of all patent filings, amounting to 17.5 million patent filings out of the total 19.4 million filings. This suggests a strong correlation between patenting and green patenting in general. We therefore construct a relative measure of green innovation, the green patent ratio, which measures the number of patents related to green technologies relative to the total number of patents held by a specific company (Bolton et al., 2023; Cohen et al., 2023; Li et al., 2024):

$$\text{Green Patent Ratio}_{f,t} = \frac{\#\text{Green Patents}_{f,t}}{\#\text{Patents}_{f,t}}$$

[22] The Y02 consists of 8 subclasses, i.e., technologies for adaptation to climate change (Y02A); climate change mitigation technologies related to buildings (Y02B); capture, storage, sequestration or disposal of greenhouse gases (Y02C); climate change mitigation technologies in ICT (Y02D); reduction of greenhouse gasses related to energy generation, transmission or distribution (Y02E); climate change mitigation technologies in the production or processing of goods (Y02P); climate change mitigation technologies related to transportation (Y02T); climate change mitigation technologies related to wastewater treatment or waste management (Y02W). We first consider all patents within the Y02 class as green patents, and verify the robustness of our results against adopting a stricter classification of green patents. Within the stricter classification, we only consider patents in the Y02E10 (renewable electricity), Y02E30 (nuclear energy) or Y02E50 (biofuels and fuel from waste) subclass as green patents.

We focus on companies that have at least one green patent in our main sample.[23] The ultimate sample consists of 3,348 unique bonds (i), issued by 361 unique companies (f) from 38 countries worldwide, which gives us 38,919 observations (N). We compare the summary statistics of firms with green patents (as reported in Table 4.2.1) to those of firms with any patent. This sample consists of 8,254 unique bonds, issued by 1,175 unique firms from 52 countries worldwide, resulting in 90,729 observations. The summary statistics for this sample are reported in Table 4.9.23 in Appendix A4.D. Compared to firms with any patent, firms that patent in green technologies (and which patent relatively more in general) tend to be larger in terms of their revenues and assets.

4.2.4 Corporate Fundamentals and Bond Characteristics

We collect information on corporate fundamentals via Refinitiv, which is also available at a quarterly frequency.[24] We also obtain information on firm's sector - and industry classification based on the Global Industry Classification Standard (GICS) and exclude all financial corporations from our analysis. Table 4.2.3 summarizes the mean emission intensity, mean green patent ratio and mean amount of green patents across sectors. A more detailed classification based on GIC Industries is provided in Appendix A2., with 49 distinct industries. There is large variation in the green patent ratio across industries. The green patent ratio is highest in the utilities sector, which also has the highest emission intensity on average. The green patent ratio is lowest in the health care sector, which has the lowest emission intensity on average. Table 4.2.3 underscores the importance of considering the number of green patents relative to the overall number of patents, as, for example, the utilities industry has the highest green patent ratio, but the number of green patents is relatively moderate compared to other industries. We also provide an overview of the issuer-countries within our sample in Appendix A2. Approximately 23.2 percent of the distinct firms in our sample are established in the

[23] We verify the robustness of our main findings in a sample which includes all companies for which patent information is available, effectively incorporating firms with a green patent ratio of zero, in Appendix A4.D.

[24] There are a few firms for which data is missing in a given quarter, which we fill with the most recent firm-observation.

GIC Sector	Observations	Emission Intensity	Green Patent Ratio	#Green Patents
Basic Materials	905	7.040	0.011	42.492
Consumer Cyclicals	609	0.638	0.011	2447.169
Consumer Non-Cyclicals	438	1.574	0.010	349.393
Energy	444	4.684	0.027	49.782
Healthcare	483	0.324	0.002	91.166
Industrials	1,060	0.983	0.012	214.147
Real Estate	55	0.912	0.004	3.182
Technology	960	0.468	0.005	886.841
Utilities	557	10.948	0.046	257.576

Note: Observations are reported at the quarterly frequency and firm-level. We report the distribution of observations across GIC Sectors and the mean of emission intensity, the green patent ratio and the number of green patents by sector.

Table 4.2.3: Distribution of observations across sectors

United States, and 35.5 percent in the European Union.

We also obtain data on daily bid- and ask prices via Refinitiv. We calculate the bid-ask spread for each bond i as the difference between the ask price and the bid price, relative to the ask price. The daily bid-ask spreads are averaged to determine the bid-ask spread at a quarterly frequency.[25]

4.3 Empirical Analysis

As a primer to our analysis, Figure 4.3.1 provides descriptive evidence on how bond markets price firms' environmental performance. Specifically, the figure plots the difference in average bond yield spreads (in the raw data) between firms in the top and bottom quintiles of the emission intensity distribution. We distinguish between firms with below- and above-median green patent ratios: the left bar shows the spread differential for firms with low green innovation, and the right bar for firms with high green innovation.

The figure suggests that there is a carbon premium, which is substantially higher among firms undertaking limited green patenting activity. In contrast, for firms with higher levels of green innovation, the yield spread differential between high- and low-emission firms is much smaller. This suggests that investors may be more willing to

[25] We obtain the bid-ask spread for approximately 93 percent of the bonds in our sample. We express the bid-ask spreads in percentages. The mean bid-ask spread is 0.407, with a standard deviation of 0.445.

Figure 4.3.1: The mean difference in observed bond yield spreads (in percentage points) between bonds issued by high- and low-emission firms. The mean difference is reported separately for firms with a below-median green patent ratio (left bar) and those with an above-median green patent ratio (right bar).

finance emission-intensive firms which undertake efforts to transition to greener technologies, reflecting the potential role of green innovation in mitigating the costs of climate-related risks.

To formally assess whether corporate bond investors reward emission-intensive firms for their efforts to transition towards greener technologies, we next examine this relationship in a regression framework. The key element in the regression model is that we interact emission intensity with a firm's relative engagement in green innovation.

4.3.1 Emission intensity, green innovation and to cost of capital

We observe each bond i, issued by a company f, in industry g, held by holder j (located in holder-country c and sector s) in year-quarter t. We estimate the following regression for the bond yield spread, measured in percentage points, at the bond-period level:

$$\begin{aligned}\text{Spread}_{i,t} = \beta_1 \text{Emission Intensity}_{f,t-1} + \beta_2 \text{Green Patent Ratio}_{f,t-1} + \beta_3 \text{Emission Intensity}_{f,t-1} \\ \cdot \text{Green Patent Ratio}_{f,t-1} + \delta' X_{f,t-1} + \gamma' Z_{i,t-1} + FE + \varepsilon_{i,t}\end{aligned} \tag{4.3.1}$$

where

$$FE = \begin{cases} \eta_f + \alpha_t & \text{(i)} \\ \eta_f + \mu_{g,t} & \text{(ii)} \end{cases}$$

and where we take the lagged value of emission intensity (Zhang, 2024), the green patent ratio and the interaction of the two. The vector of one-period lagged corporate (f) fundamentals ($X_{f,t-1}$) includes the (i) profitability ratio, defined as net income over total assets; (ii) leverage ratio, defined as total debt over total assets; (iii) cash-ratio, defined as cash over total assets; and (vi) investment ratio, defined as capital expenditures over total assets. We also include a vector of lagged bond (i) characteristics, $Z_{i,t-1}$, which includes the outstanding amount (in logarithms), a dummy which indicates if the bond has a fixed coupon, a dummy which indicates whether the bond is denominated in euro and a dummy which indicates whether the bond has a green bond label. We further verify the robustness of our main results against controlling for the bond rating, liquidity (measured by the bid-ask spread) and the bonds' maturity.[26] We estimate Equation (4.3.1) using two different sets of Fixed Effects (FE). We first use (i) firm fixed effects (η_f) and time fixed effects. This allows us to further control for unobserved, persistent firm characteristics.[27] To further strengthen the identification, we estimate the relation with (ii) industry-time fixed effects ($\mu_{g,t}$) and firm fixed effects. This allows us to absorb industry-wide time varying shocks, which is crucial as 70 percent of firms operate in tradable industries (see Table 4.7.13 in Appendix A2). We include analytical weights based on the total number of bonds outstanding of each firm in a given period in each specification.[28] We cluster standard errors at the more detailed GICS industry level (see Table 4.7.14 in Appendix A2), allowing the idiosyncratic error term $\epsilon_{i,t}$ to be

[26] Since we take a corporate perspective, we do not incorporate bond factors. For related approaches in the literature that analyze determinants of corporate bond spreads, see e.g., Dick-Nielsen, Feldhütter, and Lando (2012); Helwege, Huang, and Wang (2014); Huang and Petkevich (2016); Bauer, Derwall, and Pankratz (2021). Note that for yield spread regressions, bond factors are absent as control variables.

[27] Note that the industry dimension is nested in the firm dimension, f.

[28] Companies have on average 22.6 bonds outstanding in a given time period, and the highest number of bonds outstanding for a given company in a given period is equal to 77.

Table 4.3.4: Effect of Emission Intensity and Green Patenting on Yield Spreads

(a) Firm and Time Fixed Effects

	Bond Yield Spreads$_{i,t}$				
	(1)	(2)	(3)	(4)	(5)
Emission Intensity$_{f,t-1}$	0.126**		0.126**	0.143***	0.143***
	(0.057)		(0.057)	(0.053)	(0.053)
Green Patent Ratio$_{f,t-1}$		8.634	20.327	51.114***	51.127***
		(14.185)	(13.703)	(11.210)	(11.335)
EI$_{f,t-1}$×GPR$_{f,t-1}$				-2.419***	-2.412***
				(0.656)	(0.659)
Green Bond$_{i,t-1}$					-0.245***
					(0.074)
Corporate Fundamentals	Yes	Yes	Yes	Yes	Yes
Bond Characteristics	Yes	Yes	Yes	Yes	Yes
Time-FEs	Yes	Yes	Yes	Yes	Yes
Firm-FEs	Yes	Yes	Yes	Yes	Yes
Observations	38,979	40,203	38,979	38,979	38,979
R-squared	0.474	0.527	0.475	0.476	0.476

(b) Firm and Industry-Time Fixed Effects

	Bond Yield Spreads$_{i,t}$				
	(1)	(2)	(3)	(4)	(5)
Emission Intensity$_{f,t-1}$	0.154**		0.153**	0.199***	0.200***
	(0.073)		(0.073)	(0.056)	(0.056)
Green Patent Ratio$_{f,t-1}$		11.164	11.982	59.679***	59.823***
		(11.206)	(11.644)	(10.001)	(9.953)
EI$_{f,t-1}$×GPR$_{f,t-1}$				-3.338***	-3.340***
				(0.681)	(0.679)
Green Bond$_{i,t-1}$					-0.244***
					(0.084)
Corporate Fundamentals	Yes	Yes	Yes	Yes	Yes
Bond Characteristics	Yes	Yes	Yes	Yes	Yes
Firm-FEs	Yes	Yes	Yes	Yes	Yes
Industry-Time-FEs	Yes	Yes	Yes	Yes	Yes
Observations	38,919	40,136	38,919	38,919	38,919
R-squared	0.562	0.602	0.562	0.564	0.564

Note: OLS estimation results of Equation (4.3.1) with firm and time fixed effects (Panel A) and firm and industry-time fixed effects (Panel B). The dependent variable in all regressions is the bond yield spread (YTM in excess of the risk-free rate). Emission intensity is measured in CO2e/USDm. The green patent ratio is defined as the number of green patents owned by a given firm relative to the number of patents owned in total. '$EI \times GPR$' is the interaction of emission intensity and the green patent ratio. Green bond is a dummy variable indicating whether a bond has a green bond label. We include a set of corporate fundamentals (profitability-ratio, leverage-ratio, cash-ratio, investment-ratio) as well as bond characteristics (outstanding amount, fixed coupon dummy, euro denomination dummy). Standard errors are reported in parentheses and are clustered at the industry-level. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

correlated within industry clusters. Table 4.3.4 presents the estimation results of Equation (4.3.1). The first column shows the baseline regression where emission intensity is the sole explanatory variable. This specification estimates the carbon premium – the extent to which bond yield spreads increase with a firm's emission intensity.[29] We find evidence of a positive carbon premium, indicating that the cost of capital is higher for more emission intensive firms. We show in Appendix A3 that this results is broadly consistent across specifications, showing that the positive association is neither driven time trends in yield spreads, nor unobserved firm heterogeneity, nor by industry-specific shocks that may influence the relationship between bond yield spreads and firm's emission intensity. In our most stringent specification – with firm fixed effects and industry-time fixed effects – a one standard deviation increase in emission intensity raises bond yield spreads by 19.4 basis points.[30] This estimate, which is in line with the results of Eskildsen et al. (2024), highlights a statistically significant and economically meaningful carbon premium.

There is some evidence that banks have started to incorporate the exposure to climate transition risk in their lending decisions and are reducing lending to emission-intensive firms (e.g., Ivanov et al., 2024; Degryse et al., 2023; Altavilla et al., 2023).[31] As lending conditions become more stringent for emission-intensive firms, these firms may rely to an increasing extent on bond markets for their debt financing. A potential concern is thus that yield spreads are higher for emission-intensive firms due to a rise in bond supply. We examine whether our results are driven by a rise in bond financing by emission-intensive firms relative to other firms by plotting the evolution of the total amount outstanding, splitting the sample based on the emission intensity of the issuing company. We do not find evidence of a disproportionate expansion in bond supply of emission-intensive companies. Figure 4.8.4 in Appendix A3.A shows that the trends

[29] While some studies document a positive relationship between carbon intensity and bond yields (e.g., Seltzer et al., 2022), suggesting investors demand compensation for transition risks, others argue that bond market investors do not price climate transition risks (e.g., Duan et al., 2023).

[30] This estimate is based on within-firm variation, which is 25.7 percent of the overall variation.

[31] Giannetti et al. (2023); Sastry et al. (2024) do not find evidence that banks are adjusting their lending behavior based on firm's environmental performance.

are comparable for firms in the the higher emission intensity quintile.[32]

The second column presents results including the green patent ratio as an explanatory variable, while column three reports results with both emission intensity and the green patent ratio included. In neither specification is the green patent ratio significant on its own.

In column four, we introduce the interaction term between the green patent ratio and emission intensity, which is our primary variable of interest (β_3). The results in column 4 show that the interaction of the green patent ratio and emission intensity (labeled '$EI \times GPR$') is significantly negative. A one-standard deviation increase in the green patent ratio reduces bond yield spreads by 3.7 basis points for a company with a mean emission intensity. This constitutes a reduction in the carbon premium of approximately 15 percent, indicating that investors reward emission-intensive companies that make an effort to transition to greener technologies.[33] Given the average amount of bonds outstanding, this amounts to a reduction in financing costs of approximately 2.5 million euro annually per firm. We further explore the dynamic evolution of the interaction between emission intensity and green innovation, by allowing the coefficient of the interaction term to vary by year. Figure 4.9.5 in Appendix A4.A plots the coefficient on the interaction of the green patent ratio and emission intensity, along with the 90 percent confidence interval, with 2016 as reference period. The interaction term is significantly from zero from 2017 onward, with the coefficient remaining stable over time.

Over our sample period, there has been a rise in green financing products, such as green bonds (Flammer, 2021). Prior research (e.g., Zerbib, 2019) shows that green bonds typically trade at a yield discount, commonly referred to as the "greenium". To ensure that our findings are not driven by the presence of green bonds in our sample, we explicitly distinguish the carbon premium – the positive risk premium for exposure

[32] Figure 4.8.4 in Appendix A3.A rather shows that the amount outstanding of firms with the lowest emission intensity vastly increased over the sample period. This can partially be explained by the increase in coverage in Trucost of low-emission-intensive firms after the Paris Agreement (2016), as this increases the number of bonds of low-emission-intensive firms that appear in our sample. This observation is in line with previous literature (e.g., Bolton and Kacperczyk, 2021).

[33] This estimate again exploits the within-firm variation, which is 19 percent of the overall variation.

to carbon risk – and the yield discount related to green innovation from the greenium. We do this by controlling for whether a bond is green-labeled.[34] [35] When including this green bond indicator in column 5, our results remain consistent in both magnitude and statistical significance, confirming that the effects we identify are not confounded by the green bond yield discount.

Alternative yield measures

In Appendix A4.B, we explore several alternative yield measures. We begin with the duration-matched yield spread, which accounts for differences in bonds' sensitivity to interest rate changes (van Binsbergen, Nozawa, and Schwert, 2025).[36] The results, shown in Table 4.9.18 in Appendix A4.B, confirm that the interaction between emission intensity and green patenting remains statistically significant and negative, with a coefficient similar in magnitude to that in our baseline specification. We also examine expected yields, defined as yields adjusted for expected default losses. These can only be computed for bonds with available credit ratings.[37] The results using expected yields, which are presented in Table 4.9.19 in Appendix A4.B, yield similar results. We also confirm our findings when using yield spreads adjusted for expected default losses (Table 4.9.20), as well as when using the raw yield to maturity (Table 4.9.21).

[34] The emission intensity of green bond issuers is on average 3.294 (s.d. of 4.664) compared to an average of 2.785 (s.d. of 4.917) for non-green bond issuers.

[35] The results in column 3 indicate that bonds that qualify as green bond are associated with a large and highly significant yield discount. Note that this coefficient cannot be interpreted as estimate of the greenium within our sample, as the greenium is usually estimated by determining the average difference in yield spreads between green bonds and the most similar conventional bonds (e.g., Zerbib, 2019).

[36] For the duration matching, we focus on bonds with a fixed coupon and those denominated in euro and US dollars. We calculate the Macaulay duration using the present value of the bond's cash flows, which includes both coupon payments and the principal payment at maturity. The bond's duration is computed as the time-weighted average of the present value of cash flows, adjusted by the bond's yield and maturity. For bonds denominated in US dollars, the coupon payments and principal (which are originally denominated in euros) are adjusted by the exchange rate to account for currency differences. This ensures a consistent comparison across currencies. The average duration in our sample is 5.5 years.

[37] We use the method of Campello, Chen, and Zhang (2008); Eskildsen et al. (2024) and determine the expected bond yield by subtracting the expected default loss from the yield to maturity, where the expected default loss is computed as the probability of loss times one minus the expected recovery rate. Following Campello et al. (2008), we determine the probability of default as the average default rate over the past three years for bonds with the same rating. Following Eskildsen et al. (2024) we use the annual default rates for our seven rating categories provided by S&P Global Ratings (2023) and use recovery rates estimates from Altman, Hukkawala, and Kishore (2000).

Alternative measures of green innovation

Our estimation results indicate that investors recognize and reward the efforts emission-intensive companies make to transition towards greener technologies, as measured by their relative engagement in green innovation. To assess the robustness of this finding, we examine whether our main results hold when using several alternative measures of green innovation.

We first consider a more stringent classification of green patents, recognizing that the YO2 class in patent classification includes a broad range of technologies related to climate change mitigation and adaptation. Specifically, we focus on the Y02E subclass of the CPC, which consists of green patents aimed to reduce carbon emissions related to energy generation, transmission or distribution. We follow Acemoglu et al. (2023) who only consider a subset of innovations in the technological subclass Y02E of the CPC as green innovations.[38] This classification reduces the amount of green patents on which we obtain information to 34,231 patents, which are held by 178 unique companies.[39] The results in column 1 of Table 4.3.5 indicate that the combined effect of emission intensity and green patenting remains similar in magnitude and significance. This suggests that even when narrowly focusing on green innovations specifically targeting carbon emissions, the relationship with corporate bond yield spreads for emission-intensive firms persists.

We next examine "blockbuster" green patents, a subset of green patents that are distinguished by their high technological impact, as measured by forward citation. Specifically, we define blockbuster patents as those whose number of forward citations places them in the top 95th percentile within their respective 6-digit CPC subclass (Cohen et al., 2023). In our sample, 160 unique firms hold at least one blockbuster green patent, and approximately 5.4 percent of all green patents fall into this category. When we only consider blockbuster green patents – rather than all green patents – in

[38] Following Acemoglu et al. (2023), we only consider patents which are in the Y02E10 (renewable electricity), Y02E30 (nuclear energy) or Y02E50 (biofuels and fuel from waste) subclass as green patents.

[39] Under the stricter classification, the green patent ratio has a mean of 0.003 (s.d. of 0.012). Companies with green patents under the stricter classification have higher emissions on average. Specifically, the mean of emission intensity is 3.722 CO2 (s.d. of 5.491 CO2e).

Table 4.3.5: Robustness to Alternative Measures of Green Innovation

	Bond Yield Spreads$_{i,t}$			
	Classification (1)	Blockbusters (2)	Citations (3)	Green Innovator (4)
Emission Intensity$_{f,t-1}$	0.218***	0.160**	0.184***	0.284***
	(0.064)	(0.073)	(0.065)	(0.014)
Green Patent Ratio$_{f,t-1}$	80.271***	470.577***		
	(14.117)	(139.384)		
EI$_{f,t-1}\times$ Green Patent Ratio$_{f,t-1}$	-5.675***	-24.201***		
	(1.684)	(7.526)		
Citations Ratio$_{f,t-1}$			16.521***	
			(4.676)	
EI$_{f,t-1}\times$ Citations$_{f,t-1}$			-0.870***	
			(0.256)	
Green Firm$_{f,t-1}$				0.322**
				(0.138)
EI$_{f,t-1}\times$ Green Firm$_{f,t-1}$				-0.227***
				(0.017)
Corporate Fundamentals	Yes	Yes	Yes	Yes
Bond Characteristics	Yes	Yes	Yes	Yes
Firm-FEs	Yes	Yes	Yes	Yes
Industry-Time-FEs	Yes	Yes	Yes	Yes
Observations	19,174	37,072	37,072	38,919
R-squared	0.576	0.567	0.568	0.565

Note: Robustness tests for Equation 4.3.1, estimated by OLS with firm and industry-time fixed effects. The dependent variable in all regressions is the bond yield spread (YTM in excess of the risk-free rate). Emission intensity is measured in CO2e/USDm. The green patent ratio is defined as the number of (all, strictly classified, or blockbuster) green patents owned by a given firm relative to the number of patents owned in total. $''EI \times GPR''$ is the interaction of emission intensity and the green patent ratio. The citations ratio is defined as the total number of citations obtained on the green patents issued in a given year by the firm, relative to the total number of total patents owned by the firm on an annual basis. $'EI \times Citations'$ is the interaction of emission intensity and the citations ratio. Green firm is a dummy variable indicating whether a firm has an above median green patent ratio. We include a set of corporate fundamentals, i.e., the profitability-ratio, leverage-ratio, cash-ratio, and investment-ratio, as well as bond characteristics, i.e., the outstanding amount, a dummy for fixed coupon bonds, a dummy for euro denominated bonds, and a dummy for green bond. Standard errors are reported in parentheses and are clustered at the industry-level. *** p<0.01, ** p<0.05, * p<0.1.

constructing our relative measure of environmental performance, the results strengthen in magnitude, as shown in column 2 of Table 4.3.5. This suggests that the effect of green innovation on bond yield spreads is more pronounced when focusing on patents with

greater technological significance.

To further assess the technological relevance of green innovation, we also examine the number of forward citations received by green patents, a standard proxy for a patent's technological impact and influence. Forward citations reflect how frequently a given patent is cited by subsequent patents, thereby capturing its contribution to technological progress.[40] In our sample, a green patent receives on average 3.5 forward citations. We normalize the forward citations by the total number of patents. This measure – which we refer to as the citations-ratio – captures how impactful the green patents of a firm are relative to the its overall patent portfolio. We interact the citations-ratio with emission intensity, to capture whether the "quality" of a firm's green patents affects the relation between its emission intensity and bond yield spreads. As reported in column 3 of Table 4.3.5, the interaction term is negative and statistically significant, indicating that the effect of green innovation is stronger when the green patents are of higher technological relevance.

We further test the robustness of our results using a dummy variable indicating whether a firm is a "green innovator", defined as having an above-median green patent ratio. The results, reported in Column 5 of Table 4.3.5, confirm that the carbon premium is lower for green firms. Given a mean emission intensity, being a green innovating firm reduces yield spreads by 31 basis points. This again highlights the particular relevance that green innovation carries for investors – especially when it is undertaken by firms that are currently carbon intensive.

Our results primarily focus on the intensive margin of green innovation, as we limit our sample to firms that have at least one green patent. To assess the robustness of our findings, we extend the analysis to include all companies for which patent information is available, including those with no green patents – effectively incorporating firms with a green patent ratio of zero. This expands our sample to 1,176 unique firms and

[40] Given that there are many patents with zero citations, and the distribution of citations is thus highly skewed, our preferred measure of a patent's technological success is whether the patent is a blockbuster (Cohen et al., 2023). Nonetheless, we confirm that our findings are robust when using forward citations directly.

90,867 observations.[41] Including the extensive margin allows us to test whether our results hold when accounting for variation in both the presence and intensity of green innovation, thereby capturing the broader relationship between green innovation efforts and bond pricing across the full distribution of patenting activity. The results, presented in Table 4.9.24 in Appendix A4.D, show that the combined effect of emission intensity and green patenting remains consistent with our main specification.[42]

Alternative emission measures

There is an ongoing debate in the literature regarding whether emission intensity or absolute emissions provides a more accurate measure of a firm's environmental impact (e.g., Aswani et al., 2024; Zhang, 2024; Bolton and Kacperczyk, 2024). Emission intensity, which scales emissions by firm size, is often used to account for the growth of emissions with firm revenues. However, absolute emissions, which measure the total quantity of emissions, may better capture the overall environmental footprint of a firm, especially when considering large emitters. While emission intensity is particularly relevant in the bond context—reflecting a firm's environmental risk relative to its financial capacity—we assess the robustness of our findings by considering absolute emissions as an alternative measure. The results, reported in Table 4.9.26 in Appendix A4.F, show that the combined effect of absolute emissions and green patenting remains statistically significant at the 1 percent level. Moreover, the effect is substantially larger in magnitude when using absolute Scope 1 and 2 emissions, suggesting that the impact of emissions on bond yield spreads is even more pronounced when measured in absolute terms. This confirms the robustness of our findings, regardless of whether emissions are measured in intensity or absolute terms.

[41] We provide summary statistics for this sample in Table 4.9.23 in Appendix A4.D. Compared to firms with green patents, firms without green patents (but with other patents) tend to be smaller in terms of their revenues and assets.

[42] Note that in the extended sample of all firms with patents the magnitude of the effect diminishes due to the introduction of many zeros in the green patent ratio.

Alternative explanations

We rule out the possibility that our results are driven by other alternative explanations. We first consider general investment or innovation activities. We control for the total number of patents a firm holds (in logarithms), as reported in column 1 of Table 4.3.6. The results show that the effect of the interaction between emission intensity and the green patent ratio remains consistent in both magnitude and significance after accounting for the total number of patents owned by the firm. In column 2 of Table 4.3.6, we include an interaction between emission intensity and the investment ratio as a control variable. This interaction term is statistically insignificant, suggesting that investment activities in general do not drive our results. In column 3, we additionally control for a firm's R&D expenditures, which we obtain from Orbis, along with the interaction between emission intensity and R&D expenditures. While the interaction between emission intensity and R&D expenditures is statistically significant and negative, our results remain robust. These findings underscore the importance of green innovation efforts by emission-intensive firms, as neither general innovation activities, R&D expenditures, nor overall investments explain the observed effects. In column 4 and column 5 of Table 4.3.6, we rule out that the Corporate Sector Purchase Programme (CSPP) of the ECB, which commenced in 2016, explains our results. The Corporate Sector Purchase Programme (CSPP) of the ECB has significantly eased financing conditions in the euro area corporate debt market. The first phase of CSPP ran from June, 2016 to December, 2018, and involved purchases of corporate sector bonds by the Eurosystem. Purchases were restarted on 1 November 2019 and continued until the end of June 2022. Over our sample period, the total amount purchased was 309.7 billion euro, with 77.16 percent of these purchases occurring in the secondary market. We verify that our results are not driven by bond eligibility for purchase under the CSPP, nor by actual purchases made by the ECB. We generate a

Table 4.3.6: Robustness to General Investment and CSPP Exposure

	Bond Yield Spreads$_{i,t}$					
	Investments and Innovation			CSPP		
	(1) Patents	(2) Investments	(3) R&D	(4) Eligibility	(5) Purchase-dummy	(6) No Weights
Emission Intensity$_{f,t-1}$	0.203***	0.229***	0.283**	0.198***	0.194***	0.141***
	(0.057)	(0.084)	(0.136)	(0.059)	(0.056)	(0.038)
Green Patent Ratio$_{f,t-1}$	58.452***	53.195***	71.478***	54.845***	55.671***	34.000***
	(9.160)	(8.901)	(14.314)	(8.852)	(8.781)	(6.219)
EI$_{f,t-1}\times$ GPR$_{f,t-1}$	-3.257***	-2.809***	-4.659**	-3.084***	-3.046***	-1.873***
	(0.635)	(0.428)	(2.154)	(0.591)	(0.592)	(0.397)
Green Bond$_{i,t-1}$	-0.246***	-0.244***	-0.243***	-0.240***	-0.239***	-0.247**
	(0.084)	(0.085)	(0.086)	(0.070)	(0.074)	(0.102)
Patents$_{f,t-1}$	-0.535*					
	(0.317)					
EI$_{f,t-1}\times$ Invest-ratio$_{f,t-1}$		-0.477				
		(0.414)				
R&D$_{f,t-1}$			0.054			
			(0.038)			
EI$_{f,t-1}\times$ R&D$_{f,t-1}$			-0.095**			
			(0.042)			
CSPP$_{i,t-1}$				-0.157**	-0.207***	
				(0.078)	(0.074)	
EI$_{f,t-1}\times$ GPR$_{f,t-1}\times$ CSPP$_{i,t-1}$				-0.268	-6.598	
				(5.354)	(8.307)	
Corporate Fundamentals	Yes	Yes	Yes	Yes	Yes	Yes
Bond Characteristics	Yes	Yes	Yes	Yes	Yes	Yes
Double Interactions	-	-	-	Yes	Yes	-
Firm-FEs	Yes	Yes	Yes	Yes	Yes	Yes
Industry-Time-FEs	Yes	Yes	Yes	Yes	Yes	Yes
Observations	38,919	38,919	32,955	38,919	38,919	38,919
R-squared	0.564	0.565	0.519	0.564	0.564	0.633

Note: Robustness tests for Equation 4.3.1, estimated by OLS with firm and industry-time fixed effects. The dependent variable in all regressions is the bond yield spread (YTM in excess of the risk free rate). Emission intensity is measured in CO2e/USDm. The green patent ratio is defined as the number of green patents owned by a given firm relative to the number of patents owned in total. ''$EI \times GPR$'' is the interaction of emission intensity and the green patent ratio. Green bond is a dummy variable indicating whether a bond has a green bond label. Patents is the natural logarithm of the total number of patents owned by a firm. '$EI \times Invest$' is the interaction of emission intensity and the investment ratio, which is one of our control variables. '$EI \times R\&D$' is the interaction of emission intensity and the firm's R&D expenditures on an annual basis. CSPP is a dummy which indicates whether a bond is eligible for purchase under CSPP (column 4) or whether the bond has been purchased under the CSPP (column 5). ''$EI \times GPR' \times CSPP$' is the interaction of emission intensity, the green patent ratio and the CSPP-dummy. While not shown, we include all pairwise interactions as controls. We include a set of corporate fundamentals, i.e., the profitability-ratio, leverage-ratio, cash-ratio, and investment-ratio, as well as bond characteristics, i.e., the outstanding amount, a dummy for fixed coupon bonds, a dummy for euro denominated bonds, and a dummy for green bond. Standard errors are reported in parentheses and are clustered at the industry-level. *** p<0.01, ** p<0.05, * p<0.1.

dummy which indicates whether a given bond in our sample is eligible for purchase

under the CSPP.[43] Within our sample, 10.2 percent of bonds are eligible for purchase under CSPP. We interact emission intensity and the green patent ratio (both separately and jointly) with the eligibility- and purchase-dummy. The results reported in column 3 and column 4, respectively. While eligibility for purchase under CSPP significantly reduced bond yield spreads, neither eligibility under CSPP nor the actual purchases made drive our main results. The key interaction of emission intensity and green patent ratio for the yield spread regression remains significant, while the interactions with CSPP are not. Specifically, the interaction of emission intensity, the green patent ratio and the CSPP dummy is insignificant in either case.[44] This indicates that CSPP is not a mechanism driving our main findings. Finally, we verify the robustness of our results against the exclusion of sampling weights in column 6.

We also re-estimate Equation 2 excluding utility sector firms in Table 4.9.22 in Appendix A4.C. The utilities sector is characterized by being highly emission-intensive, yet it also has a relatively high green patent ratio (see Table 4.2.3). Given this sector's characteristics, we verify that our results are not disproportionately influenced by firms in this sector. In this case, the combined effect of emission intensity and green patenting also remains similar in terms of magnitude in this sample, confirming the robustness of our findings against the exclusion of the utilities sector.

Role of ratings, liquidity and maturity

Bond yield spreads are significantly influenced by the bond's credit risk, liquidity, and maturity. We investigate whether the joint effect of emission intensity and green innovation on bond yield spreads could be explained by these factors, by assessing whether our findings are driven by the joint determination of conventional bond characteristics and firm's environmental performance. We include interactions between our main variables of interest and each of these relevant bond characteristics.

[43] To be eligible for purchase under the CSPP, a bond should be (i) IG rated by S&P, Moody's, Fitch or DRBS, (ii) issued by a NFC in the eurozone, (iii) denominated in euros, (iv) have a residual maturity between 6 months and 31 years, and (v) have a yield to maturity that exceeds the ECB deposit facility rate. See https://www.ecb.europa.eu.

[44] Focusing on the subset of bonds issued by firms located in the euro area results in similar outcomes.

Table 4.3.7: Robustness to Ratings, Liquidity and Maturity

	Bond Yield Spreads$_{i,t}$						
	Ratings (1)	Z-score (2)	Distress Prone (3)	Financially Stable (4)	Liquidity (5)	Maturity (6)	All (7)
Emission Intensity$_{f,t-1}$	0.199*	0.430**	0.131**	-0.036***	0.211***	0.210***	0.263**
	(0.105)	(0.165)	(0.054)	(0.012)	(0.063)	(0.057)	(0.120)
Green Patent Ratio$_{f,t-1}$	119.156**	60.482**	33.735***	-42.165**	64.632***	58.878***	119.988**
	(56.472)	(22.926)	(8.897)	(17.268)	(10.862)	(10.340)	(56.011)
EI$_{f,t-1}$×GPR$_{f,t-1}$	-4.275***	-7.406**	-1.706***	0.358	-3.784***	-3.444***	-5.012**
	(1.570)	(3.570)	(0.494)	(0.569)	(0.837)	(0.717)	(1.904)
Rating$_{i,t-1}$	0.001	0.015					0.041
	(0.115)	(0.056)					(0.100)
EI$_{f,t-1}$×GPR$_{f,t-1}$×Rating$_{i,t-1}$	-0.638	1.011					-0.499
	(0.802)	(0.690)					(0.712)
Liquidity$_{i,t-1}$					0.673***		0.337***
					(0.151)		(0.123)
EI$_{f,t-1}$×GPR$_{f,t-1}$×Liquidity$_{i,t-1}$					0.946**		-0.009
					(0.423)		(2.350)
Maturity$_{i,t-1}$						0.535***	0.472***
						(0.106)	(0.117)
EI$_{f,t-1}$×GPR$_{f,t-1}$×Maturity$_{i,t-1}$						0.781*	0.554
						(0.435)	(1.690)
Corporate Fundamentals	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Bond Characteristics	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Double Interaction	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Industry-Time-FEs	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Firm-FEs	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Observations	16,194	32,764	10,250	22,405	36,203	38,919	15,620
R-squared	0.671	0.539	0.687	0.420	0.604	0.579	0.702

Note: Robustness tests for Equation 4.3.1, estimated by OLS with firm and industry-time fixed effects. The dependent variable in all regressions is the bond yield spread (YTM in excess of the risk free rate). Emission intensity is measured in CO2e/USDm. The green patent is defined as the number of green patents owned by a given firm relative to the number of patents owned in total. $''EI \times GPR''$ is the interaction of emission intensity and the green patent ratio. The rating captures the credit rating bucket, where higher values correspond to higher levels of credit risk. Liquidity is measured using the bid-ask spread. Maturity is a dummy variable equal to 1 if the residual maturity of the bond is longer than 10 years. We include a set of corporate fundamentals, i.e., the profitability-ratio, leverage-ratio, cash-ratio, and investment-ratio, as well as bond characteristics, i.e., the outstanding amount, a dummy for fixed coupon bonds, a dummy for euro denominated bonds, and a dummy for green bond. Standard errors are reported in parentheses and are clustered at the industry-level. *** p<0.01, ** p<0.05, * p<0.1.

We first consider credit ratings to account for the possibility that bond credit ratings and environmental performance are related (Carbone et al., 2021; Seltzer et al., 2022). We control for the interactions between our main variables of interest and the credit rating class. The results are presented in column 1 of Table 4.3.7. The combined effect of emission intensity and green innovation remains statistically significant at the 5 percent level. Moreover, all interactions with bond credit ratings are insignificant. Environmental performance therefore does not differentially affects bond yield spreads based on credit ratings, suggesting that traditional credit risk models do not fully account for the impact of climate risk. Given that we have rating data for approximately 40 percent of our sample, we also construct the Altman Z-score as an alternative measure of credit risk, which is a balance sheet implied rating (Acharya et al., 2024; Altman, 2018).[45] The results are reported in column 2 and are qualitatively similar to those when using credit ratings data.

Since we are using firm fixed effects in our regressions, the interactions with ratings rely on time variation in credit ratings within firms. However, ratings tend to be rather static at the firm-level. We therefore split also our sample to estimate our model separately for firms that are closer to financial distress and those that are not. Since 40 percent of the bonds in our sample are rated and fewer than 7 percent of rated bonds carry a rating below investment grade, we rely on the balance sheet implied ratings following (Acharya et al., 2024; Altman, 2018). To define an appropriate cutoff for whether a firm is closer to financial distress, we use the range of Z-scores corresponding to bonds rated between a BBB- and BB-rating.[46]

We show the results for firm's closer to financial distress in column 3 of Table 4.3.7 and for those which are not in column 4. Our findings show that the combined effect of emission intensity and green innovation on yield spreads is concentrated in the segment of firms which are closer to financial distress. This suggests that investors price

[45] The Altman Z-score is defined as $Z = 3.25 + 6.56 \times \frac{\text{Current Assets}-\text{Current Liabilities}}{\text{Total Assets}} + 3.26 \times \frac{\text{Retained Earnings}}{\text{Total Assets}} + 6.72 \times \frac{\text{EBIT}}{\text{Total Assets}} + 1.05 \times \frac{\text{Book Value of Equity}}{\text{Total Liabilities}}$. For the purpose of constructing the Z-score, we use the relevant income statement and balance sheet items from Orbis.

[46] We verify that the Z-score increases monotonically across rating categories within our sample.

climate transition risk more strongly when firms are financially vulnerable. This is consistent with default risk channel whereby green innovation reduces firms' vulnerability to transition risks. In other words, climate transition risk becomes more salient when credit risk is already high, and green efforts are more valuable to investors when the firm is closer to the threshold of default.

We also assess whether the relationship between a firm's environmental performance and bond yield spreads varies with the bond's liquidity and maturity. We use the bid-ask spread as proxy for a bond's liquidity. As shown in column 5 of Table 4.3.7, the combined effect of emission intensity and the green patent ratio on yield spreads remains statistically significant after controlling for liquidity. Column 6 presents results by bond maturity. While yield spreads are generally higher for bonds with a residual maturity of more than 10 years, we find no meaningful variation in the effect of environmental performance on yield spreads across different maturity buckets.
In summary, the combined effect of emission intensity and the green patent ratio remains highly statistically significant, even after accounting for potential heterogeneity related to bond liquidity and maturity. While we find that the pricing effects are concentrated in the segment of firms which are closer to financial distress, we do not find a differential effect when interacting our measures of environmental performance with credit ratings. This suggests that variation in credit ratings at the firm level is too limited to identify rating-based heterogeneity in firms' climate risk exposure.

4.3.2 Linking green innovation and corporate environmental performance

Our findings indicate that investors recognize the efforts emission-intensive companies make to transition to greener technologies, as these firms experience a significantly lower carbon premium compared to their non-innovative counterparts. This suggests that investors value the efforts of emission-intensive companies to reduce their environmental impact through green innovation. To better understand the implications of this finding, we explore whether green innovation is associated with corporate en-

vironmental performance. In other words, we investigate whether investors indeed 'fund the fittest'. Following Bolton et al. (2023), we assess whether green patenting is associated with a decline in future emissions. That is, we estimate the impact of green innovation on corporate environmental performance by linking a companies' contemporaneous green innovation activity to its future emission intensity, at the one-, two- and three-year horizon. The results are reported in Appendix A5.

Overall, our results do not provide a definitive answer as to whether green innovation directly improves environmental performance. This aligns qualitatively with the findings of Bolton et al. (2023), who also do not observe that green innovation leads to emission reductions. This raises the question why investors factor green innovation into the bond pricing relationship. One possible explanation is that investors expect emission reductions to materialize over a longer time horizon. Another plausible explanation is that the ownership of green patents signals to investors that the company possesses advanced green technologies relevant to the green transition, which have positive option value. Such technologies may enhance the firm's resilience and preparedness in adapting to evolving technological conditions associated with the transition. This interpretation is consistent with the idea that investors price in the potential for future environmental improvements, viewing green innovation as a signal of reduced technological uncertainty and lower transition risk.

4.3.3 Holdership dynamics

In light of the European Union's broader efforts to promote green transition goals and the public concerns about climate change within Europe compared to other regions, we assess European investors also have a higher demand for bonds of emission-intensive firms that engage in green innovation. We compare the demand of different investor types for bonds issued by firms with a similar exposure to climate transition risk. To this end, we collapse our sample to the firm-investor-time (f, j, t) [47] and estimate the

[47] Since we observe the trades in bonds among investors in different countries and investor sectors within a given period, this increases our sample by almost fivefold.

following bond demand regression (e.g., Khwaja and Mian, 2008; Boermans and Vermeulen, 2020; Acharya et al., 2024):

$$\begin{aligned}\text{Holdings}_{f,j,t} = {} & \beta_1 \text{Emission Intensity}_{f,t-1} + \beta_2 \text{Green Patent Ratio}_{f,t-1} + \beta_3 \mathbb{1}_{\text{Investor Type}=j} \\ & + \beta_4 \text{Emission Intensity}_{f,t-1} \cdot \text{Green Patent Ratio}_{f,t-1} \cdot \mathbb{1}_{\text{Investor Type}=j} \\ & + \gamma \text{Amount Outstanding}_{f,t-1} + \lambda_{f,t} + \zeta_{c,s,t} + \nu_{f,j,t} \end{aligned} \tag{4.3.2}$$

where we include all pairwise interactions between emission intensity, the green patent ratio, and the investor-indicator as controls. We expect the parameter of interest, β_4, to be positive for institutional investors, indicating that these investors have a relatively higher demand for bonds issued by emission-intensive firms that engage in green innovation efforts. Institutional investors include insurance companies, pension funds, mutual funds, and other financial institutions, while we consider banks separately. The reference investor sectors, against which we measure the relative demand of institutional investors and banks, comprise other financial institutions, non-financial corporations, governments, and households. In our most stringent specification, we estimate the regression with firm-time ($\lambda_{f,t}$) and holder area-sector-time ($\zeta_{c,s,t}$) fixed effects.[48] Our holder area-sector-time fixed effects control for potential differential portfolio choices of investors in different holder areas and sectors. Our firm-time fixed effects control for all other potential characteristics that might interact with the portfolio choice (Acharya et al., 2024). We cluster standard errors at the industry level. The results are reported in Panel A of Table 4.3.8. We first evaluate the combined effect of emission intensity and the green patent ratio on the demand of European institutional investors generally. We interact emission intensity and the green patent ratio (both separately and jointly) with an dummy variable indicating whether the investor is an institutional investor. The results with firm-time- and holder-area-sector fixed effects are reported in column 1. Column 2 reports the results of our most stringent specification, with firm-time- and holder-area-sector-time fixed effects. Our interaction effect is positive and statistically

[48] Note that all corporate fundamentals are absorbed in this specification.

Table 4.3.8: Bond Demand, Emission Intensity and Green Innovation

Panel A	$\text{Holdings}_{f,j,t}$					
	Institutional Investors			Banks		
	(1)	(2)	(3)	(4)	(5)	(6)
$\text{EI}_{f,t-1} \times \text{GPR}_{f,t-1} \times \text{Inst.}_{j,t-1}$	0.701***	0.987***	0.989***			
	(0.227)	(0.284)	(0.299)			
$\text{EI}_{f,t-1} \times \text{GPR}_{f,t-1} \times \text{Bank}_{j,t-1}$				0.211	0.569**	0.547**
				(0.131)	(0.230)	(0.220)
Amount Outstanding	Yes	Yes	Yes	Yes	Yes	Yes
Firm-Time FEs	Yes	Yes	Yes	Yes	Yes	Yes
Holder Area-Sector FEs	No	Yes	No	No	Yes	No
Holder Area-Sector-Time FEs	No	No	Yes	No	No	Yes
Observations	185,343	185,343	185,271	185,343	185,343	185,271
R-squared	0.198	0.650	0.658	0.115	0.649	0.657

Panel B	$\text{Holdings}_{f,j,t}$		
	Insur.	Mfund.	Pfund.
	(1)	(2)	(3)
$\text{EI}_{f,t-1} \times \text{GPR}_{f,t-1} \times \text{Insur.}_{j,t-1}$	0.362		
	(0.395)		
$\text{EI}_{f,t-1} \times \text{GPR}_{f,t-1} \times \text{Mfund.}_{j,t-1}$		0.467***	
		(0.143)	
$\text{EI}_{f,t-1} \times \text{GPR}_{f,t-1} \times \text{Pfund.}_{j,t-1}$			0.293
			(0.205)
Amount Outstanding	Yes	Yes	Yes
Firm-Time FEs	Yes	Yes	Yes
Holder Area-Sector-Time FEs	Yes	Yes	Yes
Observations	185,271	185,271	185,271
R-squared	0.657	0.657	0.657

*Note: Estimation of Equation (4.3.2), estimated by OLS with firm-time and holder country-sector(-time) fixed effects. Column 1-3 of Panel A report the regressions of bond holding of all European institutional investors on emission intensity, measured in CO2e/USDm, the green patent ratio, and their interaction. We estimate the regression with holder area-holder sector respectively holder area-holder sector-time FEs. Column 4-6 report the regressions of bond holding of European banks on emission intensity, measured in CO2e/USDm, the green patent ratio, and an indicator variable indicating whether the holder is an institutional investor. While not reported, we include all pairwise interactions as controls. In Panel B, estimate the regressions of bond holding of specific types of institutional investors (insurance companies, mutual funds and pension funds) on emission intensity, measured in CO2e/USDm, the green patent ratio, and an indicator variable indicating the type of the institutional investor. We include the total bond amount outstanding of the firm as control variable. Standard errors are reported in parentheses and are clustered at the industry-level. *** p<0.01, ** p<0.05, * p<0.1.*

significant at the one percent significance level for institutional investors, across all

specifications. This indicates that European institutional investors hold more bonds of emission-intensive firms that engage in green innovation, relative to the average investor within our sample. Specifically, institutional investors hold 1.9 percent more bonds of firm's with an average emission intensity and green patent ratio, compared to other investors in our sample. This suggests that these investors are more willing to finance firms that taking steps to transition to greener technologies.

To determine which of the institutional investors is driving this effect, we estimate our most stringent specification for each type of institutional investor separately in Panel B of Table 4.3.8. Our findings show that the effect of institutional investors is driven by European mutual funds, who hold 0.9 percent more bonds of firm's with an average emission intensity and green patent ratio.[49] This implies that mutual funds, potentially due to their greater risk-bearing capacity, are more responsive to firms' green innovation efforts and help direct capital toward emission-intensive firms that invest in such activities. In contrast, we do not observe a similar pattern for insurance companies or pension funds, which tend to face tighter regulatory constraints.

Finally, in column 6-8 of Panel A of Table 4.3.8 we assess whether European banks have a differential demand for bonds issued by emission-intensive firms that engage in green innovation. In this case, we also find a positive and statistically significant interaction effect. While relatively smaller in magnitude compared to institutional investors, this suggests that banks also hold relatively more bonds of emission-intensive firms that engage in green innovation compared to the average investor.

Do holdings influence yield spreads in relation to environmental performance?

We assess whether the holdings of European investors influence the extent to which environmental performance is reflected in bond yield spreads. That is, we examine

[49] This result is robust to excluding the holdings of investors based in offshore financial centers (OOFCs) in Luxembourg and Ireland (Beck, Coppola, Lewis, Maggiori, Schmitz, and Schreger, 2024). Interestingly, we observe qualitatively similar – yet quantitatively stronger – results when focusing specifically on mutual funds located in these offshore financial centers, suggesting that the demand we identify may not be unique to European investors. While only suggestive—since we do not directly observe the demand of all foreign investors—this finding is consistent with the survey evidence of Edmans et al. (2024).

whether the yield spreads of firm with comparable environmental profiles differs depending on the ownership of bonds by (different types of) European investors.[50] To measure the holdings of each respective investor, we follow Crosignani et al. (2020) and construct the "holder share":

$$\text{Holder Share}_{i,j,t} = \frac{\frac{\text{Bond Holdings}_{i,j,t}}{\text{Amount Outstanding}_{i,t}}}{\frac{\sum_i \text{Holdings}_{i,j,t}}{\sum_i \sum_j \text{Holdings}_{i,j,t}}}$$

The numerator measures the holdings of a specific European investor sector j of a given bond i relative to the total amount outstanding (at market values) in a given period t.[51] To take into account the size of the investor sector, we divide the numerator by the total holdings of the investor sector relative to the total holdings in that given period.[52] For our worldwide sample of corporate bonds, the holder share of European investors has a mean equal to 0.34 (s.d. of 0.375), signifying the large ownership of European investors in corporate bond markets globally.[53] Most of the European investments in corporate bonds stem from institutional investors, of which the holder share is on average 0.32. The average holdings of banks relative to the total amount outstanding (i.e., the numerator of the holder share) in a given period is relatively small within our

[50] While some papers analyzing bond spreads use ownership data, these studies look at equity holdings of bond-issuing firms (e.g., Huang and Petkevich, 2016; Bauer et al., 2021) but not at the direct investors of the particular bond itself.

[51] Since we observe the holdings of all European investors, the remaining holdings correspond to foreign investors.

[52] Consider the following example. Pension fund X and mutual fund Y buy 100 in corporate bonds of emission-intensive firms that innovate in the green space and 100 in corporate bonds of low emission-intensive firms. The total amount outstanding of bonds of emission-intensive firms that innovate in the green space is 400 and 800 for bonds of low emission-intensive firms. When focusing solely on the numerator of the holder share, the shares held by both pension fund X and mutual fund Y are 0.25 and 0.125, respectively. However, if pension fund X is larger than mutual fund Y, holdings should be weighted by the relative size of the investor's assets to take into account that mutual fund Y has a stronger preferences for environmental performance relative to its size (i.e., mutual fund Y relatively overweights bonds of firms with a better environmental performance in their portfolio relative to their size). By simply looking at holdings, even adjusted for the amount outstanding, the two investors do not seem to value environmental performance differentially (see Crosignani et al. (2020)).

[53] Table 4.11.31 in Appendix A6.A shows that the average holdings of each investor relative to the total amount outstanding steadily declines over our sample period.

Table 4.3.9: Bond Yield Spreads and Bond Holder Dynamics

	Bond Yield Spreads$_{i,t}$						
	EU (1)	Inst. (2)	Bank (3)	Insur. (4)	Mfund (5)	Pfund (6)	All (7)
EI$_{f,t-1}$×GPR$_{f,t-1}$	-2.834***	-2.729***	-2.469***	-2.877***	-2.489***	-2.418***	-2.551***
	(0.894)	(0.893)	(0.773)	(0.873)	(0.779)	(0.819)	(0.862)
EU-share$_{i,t-1}$	0.076						
	(0.128)						
EI$_{f,t-1}$×GPR$_{f,t-1}$xEU$_{i,t-1}$	-2.514**						
	(1.014)						
Inst.-share$_{i,t-1}$		0.281**					
		(0.133)					
EI$_{f,t-1}$×GPR$_{f,t-1}$xInst.$_{i,t-1}$		-2.718**					
		(1.063)					
Bank-share$_{i,t-1}$			-0.251*				-0.415***
			(0.135)				(0.114)
EI$_{f,t-1}$×GPR$_{f,t-1}$xBank$_{i,t-1}$			1.015				1.020
			(1.724)				(1.473)
Insur.-share$_{i,t-1}$				-0.085			-0.131
				(0.114)			(0.114)
EI$_{f,t-1}$×GPR$_{f,t-1}$xInsur.$_{i,t-1}$				-2.413**			0.535
				(1.090)			(1.177)
Mfund-share$_{i,t-1}$					0.631**		0.418**
					(0.294)		(0.172)
EI$_{f,t-1}$×GPR$_{f,t-1}$xMfund$i, t-1$					-1.637*		-1.804***
					(0.838)		(0.640)
Pfund-share$_{i,t-1}$						0.233	0.032
						(0.163)	(0.101)
EI$_{f,t-1}$×GPR$_{f,t-1}$xPfund$_{i,t-1}$						-0.383	-0.769
						(1.172)	(1.365)
Corporate Fundamentals	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Bond Characteristics	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Double Interactions	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Industry-Time-FEs	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Observations	39,046	39,046	39,046	39,046	39,046	39,046	39,046
R-squared	0.433	0.432	0.442	0.433	0.432	0.431	0.452

*Note: Estimation results of Equation (4.3.3), estimated by OLS with industry-time fixed effects. The dependent variable in all regressions is the bond yield spread (YTM in excess of the risk free rate). The first column reports the effect of EU-holdership, which is measured as the total bond value held by EU-investors as a fraction of the amount outstanding. $'EI \times GPR'$ is the interaction of emission intensity and the green patent ratio (which are both included as control variable). $'EI \times GPR \times EU'$ is the interaction of emission intensity, the green patent ratio and the EU-share. While not reported, we include all pairwise interactions as controls. We re-estimate Equation (4.3.3) using the share of institutional investors in column 2, the share of holdings of banks in column 3, the share of insurance companies in column 4, the share of mutual funds in column 5, the share of pension funds in column 6, and we include the share of each institutional investors (including banks) separately in column 7. We include a set of corporate fundamentals, i.e., the profitability-ratio, leverage-ratio, cash-ratio, and investment-ratio, as well as bond characteristics, i.e., the outstanding amount, a dummy which indicates if the bond has a fixed coupon, a dummy which indicates whether the bond is denominated in euro. Standard errors are reported in parentheses and are clustered at the industry-level. *** p<0.01, ** p<0.05, * p<0.1.*

our sample. [54] We interact emission intensity and the green patent ratio with the holder

[54] The standard deviation of the holder-share of institutional investors 0.364. For banks, the standard deviation is 0.372.

share and estimate the following regression at the bond-period level:

$$\begin{aligned}\text{Spread}_{i,t} = {} & \beta_1 \text{Emission Intensity}_{f,t-1} + \beta_2 \text{Green Patent Ratio}_{f,t-1} + \beta_3 \text{Holder Share}_{j,t-1} \\ & + \beta_4 \text{Green Patent Ratio}_{f,t-1} \cdot \text{Emission Intensity}_{f,t-1} \cdot \text{Holder Share}_{j,t-1} \\ & + \delta' X_{f,t-1} + \gamma' Z_{i,t-1} + \mu_{g,t} + \nu_{i,t} \end{aligned} \tag{4.3.3}$$

where we include all pairwise interactions between emission intensity, the green patent ratio, and the holder share as controls. The parameter of interest is β_4, which we expect to be negative whenever j concerns an European institutional investor sector or European banks. This parameter captures whether European investors charge lower yield spreads for emission-intensive firms that make an effort to become green by engaging in green innovation. We include a vector of corporate fundamentals, $X_{f,t-1}$, and bond characteristics, $Z_{i,t-1}$ as control variables. Since here is limited within-firm variation in the holder shares, and all variation in emission intensity and the green patent ratio is at the firm level, we include only industry-time fixed effects ($\mu_{g,t}$) in this specification. Standard errors are clustered at the industry level.

Table 4.3.9 reports the results of Equation (4.3.3). The first column shows the effect of EU-holdership on bond yield spreads, and includes an interaction of the lagged emission intensity, green patent ratio and the share of EU-holder. The interaction effect is negative and statistically significant at the 5 percent significance level. A standard deviation increase in the share of EU-holders reduces the yield spread of a company with a mean emission intensity and mean green patent ratio by 1.8 basis points. Although the effect is marginal in economic terms, it suggests that the yield discount associated with green innovation is more pronounced when European investors hold a larger share of the bond.

We analyze the effect of holdership by European institutional investors on bond yield spreads in column 2. Column 2 of Table 4.3.9 shows that interaction of emission intensity, the green patent ratio, and the holder share of institutional investors is statistically significant at the 5 percent significance level. A standard deviation increase

in the share of holdings of institutional investors reduces the yield spread of company with a mean emission intensity and mean green patent ratio by approximately 1.9 basis points. This aligns with our finding that institutional investors have a higher demand for bonds of emission-intensive firms that engage in green innovation and thus reveals that these investors influence yield spreads in relation to climate transition risk. Column 3 shows that the interaction of our main variables of interest with the holder share of banks is statistically insignificant. While our demand estimation did indicate that banks have a higher demand for bonds of emission intensive firms that engage in green innovation, this can potentially be explained by the fact that banks' holdings are too small at a global level to significantly affect corporate bond yield spreads. Similar to our demand estimation, we also estimate Equation (4.3.3) for each type of institutional investor. The results are presented in columns 4-6 of Table 4.3.9. Column 4 shows the effect of holdership by insurance companies, and the effects of holdership by mutual funds and pension funds are reported in columns 5 and 6, respectively. We find that holdership by insurance companies and mutual funds both have statistically significant effects on bond yield spreads. We run a horse-race by including interactions with all investor types simultaneously in column 7. Consistent with our demand estimates, only the interaction between emission intensity, the green patent ratio, and the share of holdings by mutual funds remains statistically significant. The effect is negative, indicating that the demand from European mutual funds for bonds issued by emission-intensive firms engaging in green innovation also has pricing implications. In particular, mutual fund holdings influence the extent to which environmental performance is reflected in bond yield spreads, effectively lowering these firms' cost of capital.

Risk or preferences?

Our results show that mutual funds have a relatively higher demand for bonds issued by emission-intensive firms that engage in green innovation. Given the substantial

increase in flows to European sustainable funds over our sample period.[55], this raises the question whether such demand is primarily driven by green mutual funds. While the SHS data allows us to identify bond holdings at the investor sectoral level, it does not provide sufficient granularity to determine which individual fund holds a given bond. As a result, we are unable to directly attribute observed demand to green mutual funds. To assess whether their higher demand reflects funds' green preferences or is consistent with risk pricing, we therefore turn to an alternative approach. Specifically, we determine a firm's exposure to aggregate climate risk and assess whether the effect of emission intensity (and of emission intensity combined with the green patent ratio) on bond yield spreads is stronger for firms with a larger exposure to climate risk.

We draw on the stock-holdings dataset from the SHS, which contains aggregated stock-holdings by financial and non-financial investors across euro area countries (c_s).[56] Similar to the bond-holdings dataset, the stock data are reported at the security-by-security level on a quarterly basis for stocks issued globally. For each period (t_q), we observe the value of stock holdings by a specific investor (s), identified at the country-sector level. Our analysis focuses on firms included in the bond-holdings sample. For these firms, the stock-holdings dataset provides quarterly market capitalization, along with stock prices reported for each month within the quarter, which we use to compute monthly stock returns.[57]

We use the Climate Change News Index developed by Engle et al. (2020) as an aggregate measure of climate risk. The Climate Change News Index tracks the number of news articles mentioning climate change negatively, subtracting the number of times it is mentioned positively on a given day. We use the Climate Change News Index constructed based on news articles in the New York Times, rather than the Index based on news articles in the Wall Street Journal (which is originally done in Engle et al. (2020)),

[55] For example, Morningstar reports that European sustainable fund launches and assets under management have risen substantially since 2016. Sustainable fund assets reached nearly 882 euro billion in 2020-Q3, accounting for 9.3 percent of total European fund assets. Net inflows represented approximately 40 percent of all fund flows during this period (Source: Morningstar Direct, September 2020).

[56] Given that the majority of firms in our sample are headquartered in Europe, the SHS offers the most comprehensive and complete dataset for our analysis.

[57] To mitigate the impact of outliers, we winsorize the monthly stock returns at the 99th percentile.

given that the latter series only covers part of our sample period.[58] To capture innovations in climate news, we follow Engle et al. (2020) and average the daily values of the Climate Change News Index at the monthly level. We then construct the innovations in the index as residuals from an AR(1) model. These innovations capture the unexpected component in the intensity of climate change discussions in newspapers. Based on the assumption that media coverage of climate change tends to rise when climate risk is perceived to be high – or, in other words, based on the assumption that the Climate Change News Index co-moves with climate risk –, this measure allows us to capture exogenous changes in climate-related concerns and use them as a measure of aggregate climate risk. We augment the dataset with annual corporate fundamentals from Orbis, focusing on the variables relevant for explaining stock returns.[59] Finally, we retrieve market betas from Refinitiv, which are estimated based on daily return data. Summary statistics are reported in Table 4.11.33 in Appendix A6.B.

We observe each stock i, issued by a company f, in industry g, in year-month t_m. We estimate the following regression for the stock returns, measured in percentage points, at the firm-period level:

$$\text{Stock Return}_{f,t} = \beta \text{Climate Risk}_{t-1} + \delta' X_{f,t-1} + \theta_g + \alpha_t + \epsilon_{f,t} \tag{4.3.4}$$

The vector of control variables includes: the (i) market capitalization (in logarithms); (ii) the return on equity (RoE), defined as net income divided by shareholders' equity; (iii) book-to-market ratio, defined as (book value per share times shares outstanding) divided by (market price per share times shares outstanding); (iv) leverage ratio, defined as total debt over total assets; (v) investment ratio (winsorized at 2.5 percent), defined as the year-over-year growth rate of tangible assets; (vi) property, plant and

[58] The Climate Change News Index is available online via https://www.biodiversityrisk.org.

[59] Following Kalemli-Özcan, Laeven, and Moreno (2022), we drop firm-year observations for which current assets, total equity, short-term debt, long-term debt, revenue or book value per share have negative values. We also drop the observations for which total debt (defined as short- plus long-term debt) exceeds total assets).

equipment (PPE), defined as tangible assets (in logarithms); (vii) sales growth, defined as the year-over-year growth rate of the firm's revenue; (viii) earnings-per-share (EPS) growth, defined as the annual change in the firm's EPS normalized by the firm's stock price; (ix) the market beta, defined as the CAPM beta calculated over a 12-month period using daily data; and (x) the volatility of the firm's stock, defined as the standard deviation of stock returns based on the past 12 months of monthly returns. We estimate Equation 4.3.4 using industry fixed effects (θ_g) and time fixed effects (α_t). We cluster standard errors at the industry level. This estimation is closely related to the methodology from Bolton and Kacperczyk (2021), where we use the innovations in the climate index as a measure of (aggregate) climate risk.

The estimation results of Equation 4.3.4 are presented in column 1 of Table 4.3.10. This column reports the results of the stock return regression on the climate risk measure, while controlling for other fundamental drivers of stock returns. The coefficient on climate risk is positive and statistically significant at the 5 percent significance level, indicating that, within a given industry, firms tend to experience higher stock returns on average during periods of elevated climate risk. This confirms the relevance of the climate risk measure in explaining stock returns.

We measure a firm's exposure to aggregate climate risk — which we refer to as the Climate Beta — by estimating the sensitivity of its stock returns to innovations in the Climate Change News Index, using a 12-month rolling window based on Equation 4.3.4. We take the average Climate Beta over the quarter and scale the measure by a factor $1/100$.[60] We incorporate the Climate Betas into our bond-holdings dataset and interact the measure with emission intensity and the green patent ratio, both separately and jointly. These interactions allow us to assess whether the effect of environmental performance on bond yield spreads is stronger for firms with a larger exposure to climate risk. If the interactions load significantly, this suggests that the pricing of environmental performance reflects risk-based considerations. Conversely, insignificant interactions suggest that the observed pricing effects are more likely to reflect investor

[60] We report summary statistics for the Climate Beta in Table 4.11.34 in Appendix A6.B.

Table 4.3.10: Effect of Emission Intensity and Green Patenting on Yield Spreads

	Stock Returns$_{f,t}$	Bond Yield Spreads$_{i,t}$
	Climate Risk	Climate Beta
	(1)	(2)
Climate Risk$_{t-1}$	0.346**	
	(0.169)	
Emission Intensity$_{f,t-1}$		0.479***
		(0.143)
Green Patent Ratio$_{f,t-1}$		173.165***
		(28.603)
EI$_{f,t-1}$×GPR$_{f,t-1}$		-9.251***
		(2.597)
Climate Beta$_{f,t-1}$		-1.082
		(0.729)
EI$_{f,t-1}$×Climate Beta$_{f,t-1}$		0.225**
		(0.103)
GPR$_{f,t-1}$×Climate Beta$_{f,t-1}$		11.943
		(7.979)
EI$_{f,t-1}$×GPR$_{f,t-1}$×Climate Beta$_{f,t-1}$		-5.510**
		(2.090)
Corporate Fundamentals	Yes	Yes
Bond Characteristics	No	Yes
Firm-FEs	No	Yes
Industry-FEs	Yes	No
Industry-Time-FEs	No	Yes
Time-FEs	Yes	No
Observations	11,611	19,614
R-squared	0.149	0.610

Note: Column 1 reports the OLS estimation results of Equation (4.3.4), which is estimated at the monthly frequency and firm level, with industry- and year-quarter fixed effects. The dependent variable is the stock return. Climate Risk captures the innovations in the Climate Change News Index. We include a set of corporate fundamentals (market capitalization, RoE, book-to-market-ratio, leverage-ratio, investment-ratio, PPE, sales growth, EPS-growth, market beta, and stock volatility). Standard errors are reported in parentheses and are clustered at the industry-level. Column 2 reports the OLS estimation results of Equation (4.3.1), estimated at the quarterly frequency and the bond-level, with firm and industry-time fixed effects. The dependent variable in all regressions is the bond yield spread (YTM in excess of the risk-free rate). Emission intensity is measured in CO2e/USDm. The green patent is defined as the number of green patents owned by a given firm relative to the number of patents owned in total. 'EI × GPR' is the interaction of emission intensity and the green patent ratio. Climate Beta is the firm exposure to climate risk. Green bond is a dummy variable indicating whether a bond has a green bond label. We include a set of corporate fundamentals (profitability-ratio, leverage-ratio, cash-ratio, investment-ratio) as well as bond characteristics (outstanding amount, fixed coupon dummy, euro denomination dummy, greenbond dummy). Standard errors are reported in parentheses and are clustered at the industry-level. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

preferences rather than risk compensation. The results are displayed in columns 2 of Table 4.3.10. The results in column 2 reveals that the interaction of emission intensity and the Climate Beta is positive and statistically significant at the 5 percent significance level. This indicates that the carbon premium is higher for firms that have a larger exposure to climate risk. At the same time, the reduction in the carbon premium due to green innovation is larger for firms with a higher exposure to climate risks, as the interaction of emission intensity, the green patent ratio, and the Climate Beta is negative. In other words, for firms that are more vulnerable to climate risk, investors place greater value on efforts to transition, as measured by their green patenting activity.

This evidence points toward risk pricing as the primary channel through which environmental performance influences bond yield spreads. While we did not observe that environmental performance differentially affects bond yield spreads based on credit ratings, our results show that investors do price these risks, particularly through firm's climate risk exposure as measured by the Climate Beta. This highlights the importance of incorporating climate risk in credit assessments and investment decisions more dynamically.

4.4 Conclusion

The urgency to meet the temperature targets set by the Paris Agreement necessitates a shift towards net-zero emissions by 2050. Financial investors may anticipate the associated climate transition risks and could contribute to the green transition by providing cheaper financing for firms making an effort to transition towards greener technologies. We investigate whether European corporate bond investors have taken up this role in the years following the Paris Agreement.

Specifically, we study whether corporate bond investors value companies' green innovation efforts in the presence of climate transition risk, and which investors do so. Recognizing that emission metrics are backward-looking, we complement emission intensity with a forward-looking measure of firms' climate efforts: their share of green

innovation, captured through the ratio of green to total patents. We study whether bond markets price this interaction—penalizing firms for current emissions while rewarding credible commitments to transition through innovation.

Our findings confirm the presence of a carbon premium: firms with higher emissions face higher bond yield spreads. However, this premium is significantly attenuated for firms that combine high emissions with strong green innovation efforts. These results are robust across alternative specifications, including stricter green patent definitions, the use of blockbuster patents, and controls for broader investment and patenting activity. Importantly, the effects are not driven by eligibility or purchases of corporate bonds under the ECB's Corporate Sector Purchase Programme.

Finally, our results show that institutional investors –especially mutual funds– have a higher demand for bonds issued by transitioning firms. These investors appear to price transition risk rather than responding to sustainability preferences, suggesting that investors with greater risk-bearing capacity are pivotal in channeling capital toward firms that are currently brown but actively transitioning. Our results underscore that investors respond not only to current emission levels but also to efforts to reduce them, highlighting the importance of supporting firms that are actively transitioning rather than focusing solely on already green firms.

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Appendix

4.6 Time Series Properties

Bond Yield

We estimate the following second-order autoregressive panel data model:

$$\text{Yield to Maturity}_{i,t} = \rho_1 \text{Yield to Maturity}_{i,t-1} + \rho_2 \text{Yield to Maturity}_{i,t-2} + \varsigma_i + \alpha_t + \epsilon_{i,t}$$

Table 4.6.11: Autocorrelation in Bond Yields

	OLS	FE	GMM
Yield to Maturity$_{i,t-1}$	0.768**	0.566**	0.559**
	(0.006)	(0.002)	(0.017)
Yield to Maturity$_{i,t-2}$	0.178**	0.115**	0.106**
	(0.006)	(0.004)	(0.007)

*Note: Standard errors in parentheses, ** p<0.05, * p<0.1.*

where ς_i are bond fixed effects, and α_t are time fixed effects. We estimate the model by (i) pooled OLS, (ii) fixed effects OLS and (iii) first-differenced GMM. While pooled OLS only controls for time effects, fixed effects OLS and first-difference GMM also control for the bond specific effects. Standard errors are clustered at the bond level.

Table 4.6.11 shows that there is significant autocorrelation in yields, even when including fixed effects as well as when estimating the relationship using GMM. The pooled OLS estimate, which only corrects for aggregate time effects, suggests that bond yields are highly persistent over time. The fixed effects OLS and GMM estimates, however, show that there is no reason to assume that bond yields are nonstationary. We therefore continue our estimation in levels, rather than in first-differences.

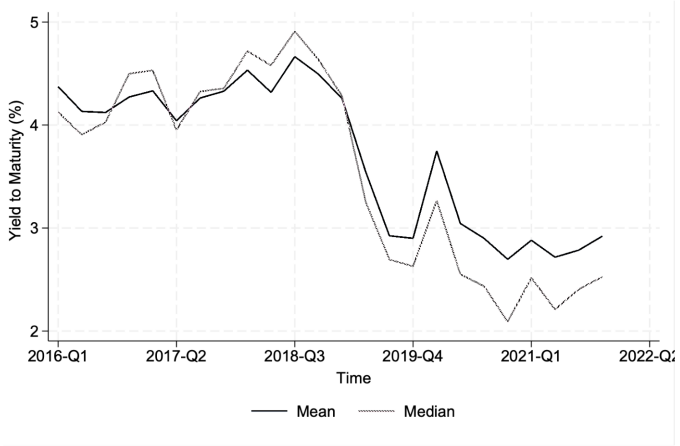


Figure 4.6.2: The evolution of the mean and median yield to maturity, reported at the quarterly-frequency and bond-level over the sample period.

Table 4.6.12: Autocorrelation in Emission Intensity

	OLS	FE	GMM
Emission Intensity$_{f,t-1}$	0.667**	0.052**	0.081
	(0.101)	(0.022)	(0.311)
Emission Intensity$_{f,t-2}$	0.281**	-0.010	0.429**
	(0.097)	(0.023)	(0.127)

*Note: Standard errors in parentheses, ** p<0.05, * p<0.1.*

Emission Intensity

To assess the time series properties of emission intensity, we first collapse our sample to the firm-period level. We again use a second-order autoregressive model:

$$\text{Emission Intensity}_{f,t} = \rho_1 \text{Emission Intensity}_{f,t-1} + \rho_2 \text{Emission Intensity}_{f,t-2} + \eta_f + \alpha_t + \epsilon_{f,t}$$

where η_f are firm fixed effects and α_t are time fixed effects. We estimate the model by the same three methods as before and standard errors are clustered at the firm-level. Table 4.6.12 displays the results. The pooled OLS estimate, which only corrects for aggregate time effects, suggests that emission intensity is persistent over time. However, the autocorrelation pattern weakens significantly when controlling for firm fixed effects as is apparent from the fixed effects OLS and GMM estimates. There is no sign that the emission intensity variable is non-stationary as the autoregressive estimates are far from the unit root.

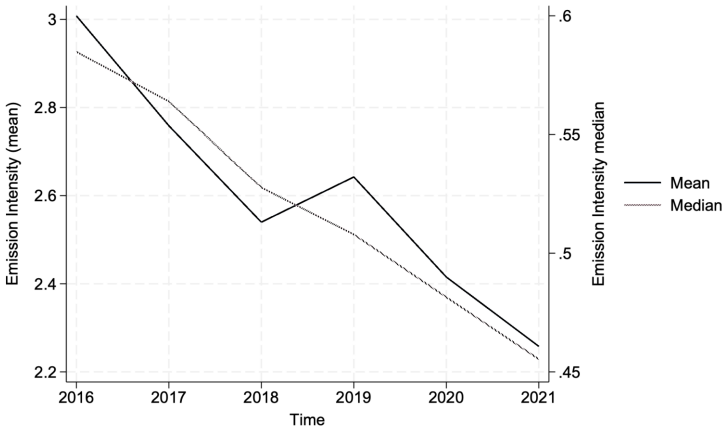


Figure 4.6.3: The evolution of the mean and median emission intensity, reported at the firm-year level over the sample period.

4.7 Additional Summary Statistics

Table 4.7.13: Distribution of Observations Across Industries

GICS Industry Name	Frequency	Percent	Classification
Aerospace & Defense	236	4.28	Tradable
Air Freight & Logistics	46	0.83	Tradable
Automobile Components	172	3.12	Tradable
Automobiles	212	3.85	Tradable
Beverages	66	1.20	Non-Tradable
Biotechnology	138	2.50	Tradable
Broadline Retail	54	0.98	Non-Tradable
Building Products	72	1.31	Tradable
Chemicals	448	8.13	Tradable
Commercial Services & Supplies	34	0.62	Non-Tradable
Communications Equipment	72	1.31	Tradable
Construction & Engineering	111	2.01	Non-Tradable
Construction Materials	29	0.53	Non-Tradable
Consumer Staples Distribution & Retail	105	1.91	Non-Tradable
Containers & Packaging	46	0.83	Tradable
Diversified Telecommunication Services	180	3.27	Other
Electric Utilities	368	6.68	Non-Tradable
Electrical Equipment	226	4.10	Tradable
Electronic Equipment, Instruments & Components	89	1.61	Tradable
Energy Equipment & Services	15	0.27	Tradable
Food Products	129	2.34	Tradable
Gas Utilities	46	0.83	Non-Tradable
Ground Transportation	46	0.83	Non-Tradable
Health Care Equipment & Supplies	69	1.25	Tradable
Household Durables	71	1.29	Tradable
Household Products	21	0.38	Tradable
IT Services	62	1.13	Tradable
Independent Power and Renewable Electricity Producers	79	1.43	Non-Tradable
Industrial Conglomerates	80	1.45	Tradable
Leisure Products	20	0.36	Tradable
Life Sciences Tools & Services	9	0.16	Tradable
Machinery	271	4.92	Tradable
Marine Transportation	39	0.71	Tradable
Media	46	0.83	Non-Tradable
Metals & Mining	285	5.17	Tradable
Multi-Utilities	87	1.58	Non-Tradable
Oil, Gas & Consumable Fuels	339	6.15	Tradable
Paper & Forest Products	94	1.71	Tradable
Personal Care Products	19	0.34	Tradable
Pharmaceuticals	267	4.84	Tradable
Real Estate Management & Development	30	0.54	Non-Tradable
Semiconductors & Semiconductor Equipment	311	5.64	Tradable
Software	88	1.60	Tradable
Specialized REITs	23	0.42	Non-Tradable
Technology Hardware, Storage & Peripherals	99	1.80	Tradable
Textiles, Apparel & Luxury Goods	23	0.42	Tradable
Tobacco	20	0.36	Tradable
Trading Companies & Distributors	73	1.32	Tradable
Wireless Telecommunication Services	46	0.83	Non-Tradable

Note: Distribution of observations across GICS Industries. Observations are reported at the quarterly frequency and firm-level.

Table 4.7.14: Emission Intensity and Green Patents across industries (mean)

GICS Industry Name	Emission Intensity	Green Patent Ratio	Green Patents
Aerospace & Defense	0.291	0.001	16.458
Air Freight & Logistics	1.466	0.001	3.848
Automobile Components	1.131	0.002	165.512
Automobiles	0.263	0.023	6813.118
Beverages	0.648	0.005	39.636
Biotechnology	0.291	0.002	15.659
Broadline Retail	0.322	0.009	7.796
Building Products	1.029	0.006	74.014
Chemicals	5.643	0.004	61.598
Commercial Services & Supplies	0.365	0.003	127.206
Communications Equipment	0.162	0.000	55.681
Construction & Engineering	0.496	0.014	13.631
Construction Materials	19.940	0.010	9.172
Consumer Staples Distribution & Retail	0.543	0.007	2.762
Containers & Packaging	1.469	0.001	4.500
Diversified Telecommunication Services	0.402	0.007	305.822
Electric Utilities	12.601	0.056	377.690
Electrical Equipment	0.737	0.026	233.611
Electronic Equipment, Instruments & Components	0.812	0.006	455.090
Energy Equipment & Services	1.163	0.011	1.667
Food Products	0.849	0.021	4.682
Gas Utilities	2.667	0.030	49.978
Ground Transportation	1.457	0.027	208.109
Health Care Equipment & Supplies	0.237	0.001	364.015
Household Durables	0.352	0.012	9256.761
Household Products	0.307	0.001	75.381
IT Services	0.130	0.019	156.468
Independent Power and Renewable Electricity Producers	16.167	0.023	24.848
Industrial Conglomerates	5.458	0.008	1836.225
Leisure Products	0.453	0.015	517.500
Life Sciences Tools & Services	0.384	0.000	3.111
Machinery	0.369	0.015	558.096
Marine Transportation	11.007	0.004	1.641
Media	0.120	0.002	3.000
Metals & Mining	9.319	0.028	30.705
Multi-Utilities	1.939	0.019	2.770
Oil, Gas & Consumable Fuels	5.455	0.012	24.749
Paper & Forest Products	3.332	0.004	26.319
Personal Care Products	0.331	0.000	8.000
Pharmaceuticals	0.362	0.002	62.648
Real Estate Management & Development	0.449	0.005	3.967
Semiconductors & Semiconductor Equipment	1.939	0.019	70.473
Software	0.120	0.001	3.886
Specialized REITs	1.565	0.000	2.000
Technology Hardware, Storage & Peripherals	0.182	0.002	623.879
Textiles, Apparel & Luxury Goods	0.078	0.001	22.174
Tobacco	0.387	0.004	114.700
Trading Companies & Distributors	1.026	0.015	129.370
Wireless Telecommunication Services	0.414	0.007	151.978

Note: Observations are reported at the quarterly frequency and firm-level. We report the mean of emission intensity, the green patent ratio and the number of green patents. We classify industries as tradable, non-tradable and others.

Table 4.7.15: Emission Intensity and Green Patents across industries (median)

GICS Industry Name	Emission Intensity	Green Patent Ratio	Green Patents
Aerospace & Defense	0.220	0.001	4.000
Air Freight & Logistics	1.352	0.001	5.500
Automobile Components	0.563	0.001	8.000
Automobiles	0.243	0.006	366.000
Beverages	0.477	0.002	19.000
Biotechnology	0.311	0.001	10.000
Broadline Retail	0.285	0.002	3.000
Building Products	0.777	0.001	62.000
Chemicals	4.043	0.000	10.000
Commercial Services & Supplies	0.339	0.000	1.000
Communications Equipment	0.177	0.001	68.000
Construction & Engineering	0.398	0.010	2.000
Construction Materials	19.940	0.001	3.000
Consumer Staples Distribution & Retail	0.515	0.005	2.000
Containers & Packaging	1.424	0.001	4.500
Diversified Telecommunication Services	0.373	0.002	6.000
Electric Utilities	13.960	0.048	10.000
Electrical Equipment	0.466	0.001	11.000
Electronic Equipment, Instruments & Components	0.292	0.003	15.000
Energy Equipment & Services	1.111	0.001	1.000
Food Products	0.630	0.000	2.000
Gas Utilities	3.008	0.026	40.500
Ground Transportation	1.379	0.025	189.500
Health Care Equipment & Supplies	0.131	0.001	7.000
Household Durables	0.349	0.011	5923.000
Household Products	0.309	0.001	75.000
IT Services	0.143	0.001	10.000
Independent Power and Renewable Electricity Producers	19.940	0.016	8.000
Industrial Conglomerates	0.637	0.001	6.000
Leisure Products	0.365	0.007	232.000
Life Sciences Tools & Services	0.284	0.001	2.000
Machinery	0.390	0.001	10.000
Marine Transportation	11.756	0.002	3.000
Media	0.130	0.002	3.000
Metals & Mining	7.456	0.003	8.000
Multi-Utilities	1.399	0.013	1.000
Oil, Gas & Consumable Fuels	4.884	0.003	12.000
Paper & Forest Products	3.074	0.004	35.000
Personal Care Products	0.332	0.000	8.000
Pharmaceuticals	0.242	0.001	25.000
Real Estate Management & Development	0.388	0.008	7.000
Semiconductors & Semiconductor Equipment	0.752	0.000	13.000
Software	0.099	0.001	4.000
Specialized REITs	1.526	0.000	2.000
Technology Hardware, Storage & Peripherals	0.110	0.001	3.000
Textiles, Apparel & Luxury Goods	0.083	0.001	22.000
Tobacco	0.391	0.005	123.000
Trading Companies & Distributors	0.735	0.016	149.000
Wireless Telecommunication Services	0.385	0.008	172.000

Note: Observations are reported at the quarterly frequency and firm-level. We report the median of emission intensity, the green patent ratio and the number of green patents.

Table 4.7.16: Distribution of observations across countries

Country	Frequency	Percent
United Arab Emirates	23	0.42
Austria	58	1.05
Australia	22	0.40
Belgium	94	1.71
Brazil	72	1.31
Canada	135	2.45
Switzerland	194	3.52
Chile	23	0.42
China	167	3.03
Colombia	23	0.42
Czech Republic	23	0.42
Germany	401	7.28
Denmark	23	0.42
Spain	122	2.21
Finland	209	3.79
France	383	6.95
United Kingdom	181	3.28
Hong Kong	23	0.42
Hungary	23	0.42
India	136	2.47
Italy	160	2.90
Japan	639	11.59
South Korea	220	3.99
Luxembourg	54	0.98
Malaysia	23	0.42
Netherlands	162	2.94
Norway	164	2.98
New Zealand	23	0.42
Philippines	6	0.11
Poland	24	0.44
Russia	87	1.58
Saudi Arabia	7	0.13
Sweden	218	3.96
Singapore	13	0.24
Thailand	9	0.16
Turkey	50	0.91
Taiwan	39	0.71
United States	1,278	23.19

Note: Distribution of observations across countries. Observations are reported at the quarterly frequency and firm-level.

4.8 Carbon premium regression

Table 4.8.17: The Effect of Emission Intensity on Yield Spreads

	Bond Yield Spreads$_{i,t}$								
	Time FEs			Firm + Time FEs			Firm + Industry-Time FEs		
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
Emission Intensity$_{f,t-1}$	0.104***	0.083**	0.083**	0.128**	0.126**	0.126**	0.141**	0.154**	0.154**
	(0.038)	(0.039)	(0.039)	(0.055)	(0.057)	(0.057)	(0.062)	(0.073)	(0.073)
Green Bond$_{i,t-1}$			-0.290**			-0.246***			-0.242***
			(0.114)			(0.079)			(0.089)
Corporate Fundamentals	No	Yes	Yes	No	Yes	Yes	No	Yes	Yes
Bond Characteristics	No	Yes	Yes	No	Yes	Yes	No	Yes	Yes
Time-FEs	Yes	Yes	Yes	Yes	Yes	Yes	No	No	No
Firm-FEs	No	No	No	Yes	Yes	Yes	Yes	Yes	Yes
Industry-Time-FEs	No	No	No	No	No	No	Yes	Yes	Yes
Observations	39,023	39,011	39,011	38,991	38,979	38,979	38,931	38,919	38,919
R-squared	0.153	0.225	0.226	0.460	0.474	0.475	0.547	0.562	0.562

Note: OLS estimation results. The dependent variable in all regressions is the bond yield spread (YTM in excess of the risk free rate). We exploit three different sets of fixed effects, i.e., time fixed effects (column 1-3), firm fixed effects and time fixed effect (column 4-6), and firm fixed effects and industry-time fixed effects (column 7-9). For each set of fixed effects, the first column reports the results of a simple regression using emission intensity as explanatory variable, which is measured in CO2e/USDm. The second column reports the results when including control variables. We include a set of corporate fundamentals, i.e., the profitability-ratio, leverage-ratio, cash-ratio, and investment-ratio, as well as bond characteristics, i.e., the outstanding amount, a dummy which indicates if the bond has a fixed coupon, a dummy which indicates whether the bond is denominated in euro. The third column additionally controls for whether a bond has a green bond label. Standard errors are reported in parentheses and are clustered at the industry level. *** p<0.01, ** p<0.05, * p<0.1.

4.8.1 Evolution of bond supply

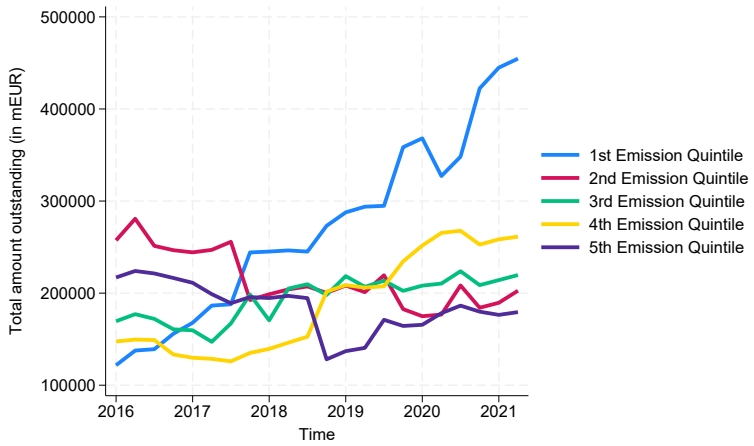


Figure 4.8.4: The evolution of total amount outstanding (in m EUR) by emission quintile over the sample period.

4.9 Robustness and Additional Tests for Equation (2)

4.9.1 Dynamic plot of the main coefficient

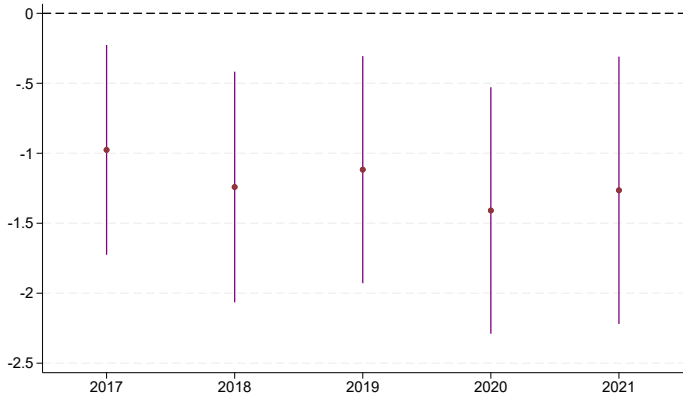


Figure 4.9.5: Dynamic plot of the coefficient for the interaction of emission intensity and the green patent ratio ($EI \times GPR$), along with the 90 percent confidence intervals. The reference period is 2016.

4.9.2 Alternative yield measures

Table 4.9.18: Effect of Emission Intensity and Green Patenting on Yield Spreads

	Bond Yield Spreads$_{i,t}$				
	(1)	(2)	(3)	(4)	(5)
Emission Intensity$_{f,t-1}$	0.173		0.173	0.215**	0.214**
	(0.111)		(0.111)	(0.094)	(0.095)
Green Patent Ratio$_{f,t-1}$		1.474	1.490	46.140**	46.155**
		(2.444)	(3.431)	(21.531)	(21.624)
EI$_{f,t-1}$ × GPR$_{f,t-1}$				-3.091**	-3.091**
				(1.235)	(1.238)
Green Bond$_{i,t-1}$					0.074
					(0.054)
Corporate Fundamentals	Yes	Yes	Yes	Yes	Yes
Bond Characteristics	Yes	Yes	Yes	Yes	Yes
Industry-Time-FEs	Yes	Yes	Yes	Yes	Yes
Firm-FEs	Yes	Yes	Yes	Yes	Yes
Observations	24,584	25,069	24,584	24,584	24,584
R-squared	0.665	0.653	0.665	0.666	0.667

Note: OLS estimation results of Equation (4.3.1) with firm and industry-time fixed effects. The dependent variable in all regressions is the expected yield spread (YTM in excess of the duration-matched risk-free rate). Emission intensity is measured in CO2e/USDm. The green patent is defined as the number of green patents owned by a given firm relative to the number of patents owned in total. 'EI × GPR' is the interaction of emission intensity and the green patent ratio. Green bond is a dummy variable indicating whether a bond has a green bond label. We include a set of corporate fundamentals (profitability-ratio, leverage-ratio, cash-ratio, investment-ratio, revenue) as well as bond characteristics (outstanding amount, fixed coupon dummy, euro denomination dummy). Standard errors are reported in parentheses and are clustered at the industry-level. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

Table 4.9.19: Effect of Emission Intensity and Green Patenting on Expected Yields

	Bond Yield Spreads$_{i,t}$				
	(1)	(2)	(3)	(4)	(5)
Emission Intensity$_{f,t-1}$	0.165		0.173	0.242	0.244
	(0.143)		(0.145)	(0.156)	(0.155)
Green Patent Ratio$_{f,t-1}$		19.608	28.120	88.937**	90.791**
		(16.913)	(22.780)	(33.152)	(33.652)
EI$_{f,t-1}$ × GPR$_{f,t-1}$				-4.143**	-4.200**
				(1.872)	(1.880)
Green Bond$_{i,t-1}$					-0.474***
					(0.153)
Corporate Fundamentals	Yes	Yes	Yes	Yes	Yes
Bond Characteristics	Yes	Yes	Yes	Yes	Yes
Industry-Time-FEs	Yes	Yes	Yes	Yes	Yes
Firm-FEs	Yes	Yes	Yes	Yes	Yes
Observations	16,888	17,181	16,888	16,888	16,888
R-squared	0.620	0.613	0.620	0.621	0.621

Note: OLS estimation results of Equation (4.3.1) with firm and industry-time fixed effects. The dependent variable in all regressions is the expected yield (YTM corrected for the expected default loss). Emission intensity is measured in CO2e/USDm. The green patent is defined as the number of green patents owned by a given firm relative to the number of patents owned in total. 'EI × GPR' is the interaction of emission intensity and the green patent ratio. Green bond is a dummy variable indicating whether a bond has a green bond label. We include a set of corporate fundamentals (profitability-ratio, leverage-ratio, cash-ratio, investment-ratio, revenue) as well as bond characteristics (outstanding amount, fixed coupon dummy, euro denomination dummy). Standard errors are reported in parentheses and are clustered at the industry-level. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

Table 4.9.20: Effect of Emission Intensity and Green Patenting on Expected Yield Spreads

	Bond Yield Spreads$_{i,t}$				
	(1)	(2)	(3)	(4)	(5)
Emission Intensity$_{f,t-1}$	0.194		0.199	0.250	0.252
	(0.150)		(0.153)	(0.160)	(0.159)
Green Patent Ratio$_{f,t-1}$		8.926	18.316	63.682**	65.017**
		(12.280)	(16.848)	(26.410)	(25.789)
EI$_{f,t-1}$ × GPR$_{f,t-1}$				-3.091**	-3.132**
				(1.386)	(1.358)
Green Bond$_{i,t-1}$					-0.342***
					(0.108)
Corporate Fundamentals	Yes	Yes	Yes	Yes	Yes
Bond Characteristics	Yes	Yes	Yes	Yes	Yes
Industry-Time-FEs	Yes	Yes	Yes	Yes	Yes
Firm-FEs	Yes	Yes	Yes	Yes	Yes
Observations	16,867	17,158	16,867	16,867	16,867
R-squared	0.599	0.587	0.599	0.600	0.601

Note: OLS estimation results of Equation (4.3.1) with firm and industry-time fixed effects. The dependent variable in all regressions is the expected yield spread (YTM in excess of the risk-free rate, corrected for the expected default loss). Emission intensity is measured in CO2e/USDm. The green patent is defined as the number of green patents owned by a given firm relative to the number of patents owned in total. 'EI × GPR' is the interaction of emission intensity and the green patent ratio. Green bond is a dummy variable indicating whether a bond has a green bond label. We include a set of corporate fundamentals (profitability-ratio, leverage-ratio, cash-ratio, investment-ratio, revenue) as well as bond characteristics (outstanding amount, fixed coupon dummy, euro denomination dummy). Standard errors are reported in parentheses and are clustered at the industry-level. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

Table 4.9.21: Effect of Emission Intensity and Green Patenting on Bond Yields

	Bond Yield Spreads$_{i,t}$				
	(1)	(2)	(3)	(4)	(5)
Emission Intensity$_{f,t-1}$	0.133		0.132	0.174**	0.175**
	(0.082)		(0.081)	(0.071)	(0.070)
Green Patent Ratio$_{f,t-1}$		15.086	15.322	59.367***	59.510***
		(11.647)	(12.212)	(15.151)	(15.401)
EI$_{f,t-1}$ × GPR$_{f,t-1}$				-3.083***	-3.084***
				(0.974)	(0.982)
Green Bond$_{i,t-1}$					-0.244
					(0.186)
Corporate Fundamentals	Yes	Yes	Yes	Yes	Yes
Bond Characteristics	Yes	Yes	Yes	Yes	Yes
Industry-Time-FEs	Yes	Yes	Yes	Yes	Yes
Firm-FEs	Yes	Yes	Yes	Yes	Yes
Observations	38,956	40,176	38,956	38,956	38,956
R-squared	0.585	0.601	0.585	0.586	0.586

Note: OLS estimation results of Equation (4.3.1) with firm and industry-time fixed effects. The dependent variable in all regressions is the yield to maturity. Emission intensity is measured in CO2e/USDm. The green patent is defined as the number of green patents owned by a given firm relative to the number of patents owned in total. 'EI × GPR' is the interaction of emission intensity and the green patent ratio. Green bond is a dummy variable indicating whether a bond has a green bond label. We include a set of corporate fundamentals (profitability-ratio, leverage-ratio, cash-ratio, investment-ratio) as well as bond characteristics (outstanding amount, fixed coupon dummy, euro denomination dummy). Standard errors are reported in parentheses and are clustered at the industry-level. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

4.9.3 Main results excluding the utilities sector

Table 4.9.22: Effect of Emission Intensity and Green Patenting on Yield Spreads

	Bond Yield Spreads$_{i,t}$				
	(1)	(2)	(3)	(4)	(5)
Emission Intensity$_{f,t-1}$	0.258***		0.254***	0.264***	0.264***
	(0.028)		(0.031)	(0.026)	(0.026)
Green Patent Ratio$_{f,t-1}$		34.730	38.679	61.739***	61.951***
		(25.427)	(25.589)	(12.430)	(12.388)
		(23.384)	(28.888)	(12.609)	(12.598)
EI$_{f,t-1}$×GPR$_{f,t-1}$				-3.825***	-3.834***
				(0.712)	(0.711)
Green Bond$_{i,t-1}$					-0.142***
					(0.044)
Corporate Fundamentals	Yes	Yes	Yes	Yes	Yes
Bond Characteristics	Yes	Yes	Yes	Yes	Yes
Firm-FEs	Yes	Yes	Yes	Yes	Yes
Industry-Time-FEs	Yes	Yes	Yes	Yes	Yes
Observations	33,617	34,834	33,617	33,617	33,617
R-squared	0.602	0.641	0.602	0.603	0.603

Note: OLS estimation results of Equation (4.3.1) with firm and industry-time fixed effects. The dependent variable in all regressions is the bond yield spread (YTM in excess of the risk-free rate). Emission intensity is measured in CO2e/USDm. The green patent is defined as the number of green patents owned by a given firm relative to the number of patents owned in total. 'EI × GPR' is the interaction of emission intensity and the green patent ratio. Green bond is a dummy variable indicating whether a bond has a green bond label. We include a set of corporate fundamentals (profitability-ratio, leverage-ratio, cash-ratio, investment-ratio) as well as bond characteristics (outstanding amount, fixed coupon dummy, euro denomination dummy). Standard errors are reported in parentheses and are clustered at the industry-level. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

4.9.4 Full sample of patenting firms

Table 4.9.23: Summary Statistics

	Mean	Median	SD	P10	P90
Environmental Variables					
(Scope1 + Scope2) Emission Intensity	2.533	0.457	4.598	0.109	8.399
(Scope1 + Scope2) Absolute Emissions (in log)	13.827	13.870	2.313	10.897	16.962
Green Patent Ratio	0.003	0.001	0.014	0.001	0.004
Bond Characteristics					
Yield to Maturity (%)	2.575	2.239	2.649	0.038	5.219
Spread (%)	1.929	1.218	2.444	0.390	4.117
Bond Holding Value (in m EUR)	170.103	50.522	260.201	1.917	527.494
Amount Outstanding (in m EUR)	580.660	467.290	510.1328	89.087	1150
Fixed Coupon	0.915	1	0.279	1	1
EUR	0.334	0	0.472	0	1
USD	0.499	0	0.500	0	1
Green bond	0.015	0	0.123	0	0
Corporate Fundamentals					
Revenue (in bn EUR)	37.491	15.614	63.996	1.656	84.853
Total Assets (in bn EUR)	62.444	28.475	80.212	3.853	171.75
Total Debt (in bn EUR)	21.198	9.611	28.197	1.214	56.846
Profitability-Ratio (%)	4.755	4.166	6.156	-0.587	11.144
Leverage-Ratio (%)	36.074	35.142	14.575	19.218	54.577
Cash-Ratio (%)	6.453	2.987	10.466	0.385	14.399
Investment-Ratio (%)	13.208	6.877	17.708	0.913	34.986

Note: Based on 90,729 observations, reported at quarterly frequency and the security-by-security level. Absolute emissions levels are measured in CO2e and are reported in natural logarithms. Emission intensity, measured in CO2e/USDm, is scaled by a factor 1/100 and winsorized at the 2.5 percent level. Yield to maturity is winsorized at the 99th percentile. Fixed coupon is a dummy which is equal to 1 if a bond has a fixed coupon. EUR respectively USD are dummy variables, which are equal to 1 if a bond is denominated in euros respectively dollars. Green bond is a dummy which is equal to 1 if a bond has a green bond label. The profitability-ratio is defined as net income dividend by total assets (ROA). Leverage is defined as total debt divided by total assets. The cash- and investment ratio are defined as cash and capital expenditures divided by total assets, respectively. All ratio's are reported in percentages.

Table 4.9.24: Effect of Emission Intensity and Green Patenting on Yield Spreads

	Bond Yield Spreads$_{i,t}$				
	(1)	(2)	(3)	(4)	(5)
Emission Intensity$_{f,t-1}$	0.115		0.115	0.126	0.126
	(0.079)		(0.080)	(0.080)	(0.080)
Green Patent Ratio$_{f,t-1}$		12.026	10.104	37.422**	37.298**
		(10.332)	(10.062)	(15.361)	(15.470)
EI$_{f,t-1}$×GPR$_{f,t-1}$				-1.974**	-1.963**
				(0.949)	(0.954)
Green Bond$_{i,t-1}$					-0.110*
					(0.062)
Corporate Fundamentals	Yes	Yes	Yes	Yes	Yes
Bond Characteristics	Yes	Yes	Yes	Yes	Yes
Firm-FEs	Yes	Yes	Yes	Yes	Yes
Industry-Time-FEs	Yes	Yes	Yes	Yes	Yes
Observations	90,747	90,807	90,729	90,729	90,729
R-squared	0.618	0.617	0.618	0.618	0.618

Note: OLS estimation results of Equation (4.3.1) with firm and industry-time fixed effects. The dependent variable in all regressions is the bond yield spread (YTM in excess of the risk-free rate). Emission intensity is measured in CO2e/USDm. The green patent is defined as the number of green patents owned by a given firm relative to the number of patents owned in total. 'EI × GPR' is the interaction of emission intensity and the green patent ratio. Green bond is a dummy variable indicating whether a bond has a green bond label. We include a set of corporate fundamentals (profitability-ratio, leverage-ratio, cash-ratio, investment-ratio) as well as bond characteristics (outstanding amount, fixed coupon dummy, euro denomination dummy). Standard errors are reported in parentheses and are clustered at the industry-level. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

4.9.5 Assigning patents based on application dates

Table 4.9.25: Effect of Emission Intensity and Green Patenting on Yield Spreads

	Bond Yield Spreads$_{i,t}$				
	(1)	(2)	(3)	(4)	(5)
Emission Intensity$_{f,t-1}$	0.154**		0.152**	0.206***	0.207***
	(0.073)		(0.073)	(0.053)	(0.053)
Green Patent Ratio$_{f,t-1}$		11.866	7.316	66.186***	66.266***
		(9.493)	(9.322)	(12.688)	(12.546)
EI$_{f,t-1}$×GPR$_{f,t-1}$				-3.797***	-3.800***
				(0.785)	(0.779)
Green Bond$_{i,t-1}$					-0.244***
					(0.084)
Corporate Fundamentals	Yes	Yes	Yes	Yes	Yes
Bond Characteristics	Yes	Yes	Yes	Yes	Yes
Firm-FEs	Yes	Yes	Yes	Yes	Yes
Industry-Time-FEs	Yes	Yes	Yes	Yes	Yes
Observations	38,919	39,063	38,919	38,919	38,919
R-squared	0.562	0.553	0.562	0.564	0.564

Note: OLS estimation results of Equation (4.3.1) with firm and industry-time fixed effects. The dependent variable in all regressions is the bond yield spread (YTM in excess of the risk-free rate). Emission intensity is measured in CO2e/USDm. The green patent is defined as the number of green patents owned by a given firm relative to the number of patents owned in total. 'EI × GPR' is the interaction of emission intensity and the green patent ratio. Green bond is a dummy variable indicating whether a bond has a green bond label. We include a set of corporate fundamentals (profitability-ratio, leverage-ratio, cash-ratio, investment-ratio) as well as bond characteristics (outstanding amount, fixed coupon dummy, euro denomination dummy). Standard errors are reported in parentheses and are clustered at the industry-level. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

4.9.6 Absolute scope 1 and 2 emissions

Table 4.9.26: Effect of Emission Intensity and Green Patenting on Yield Spreads

	Bond Yield Spreads$_{i,t}$				
	(1)	(2)	(3)	(4)	(5)
Scope 1+2 Emissions$_{f,t-1}$	0.164		0.161	0.292**	0.293**
	(0.134)		(0.135)	(0.128)	(0.127)
Green Patent Ratio$_{f,t-1}$		11.306	10.883	169.742***	171.163***
		(11.037)	(10.989)	(51.423)	(50.811)
Abs$_{f,t-1}$ × GPR$_{f,t-1}$				-9.324***	-9.396***
				(2.952)	(2.919)
Green Bond$_{i,t-1}$					-0.367**
					(0.156)
Corporate Fundamentals	Yes	Yes	Yes	Yes	Yes
Bond Characteristics	Yes	Yes	Yes	Yes	Yes
Industry-Time-FEs	Yes	Yes	Yes	Yes	Yes
Firm-FEs	Yes	Yes	Yes	Yes	Yes
Observations	39,984	40,136	39,984	39,984	39,984
R-squared	0.607	0.602	0.607	0.608	0.609

Note: OLS estimation results of Equation (4.3.1) with firm and industry-time fixed effects. The dependent variable in all regressions is the bond yield spread (YTM in excess of the risk-free rate). Emission intensity is measured in CO2e/USDm. The green patent is defined as the number of green patents owned by a given firm relative to the number of patents owned in total. 'EI × GPR' is the interaction of emission intensity and the green patent ratio. Green bond is a dummy variable indicating whether a bond has a green bond label. We include a set of corporate fundamentals (profitability-ratio, leverage-ratio, cash-ratio, investment-ratio) as well as bond characteristics (outstanding amount, fixed coupon dummy, euro denomination dummy). Standard errors are reported in parentheses and are clustered at the industry-level. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

4.10 Corporate Environmental Performance

A recent, growing literature studies whether green innovation improves environmental performance. Cohen et al. (2023) find that firms with lower ESG-scores are key innovators in the United States' green patent landscape. Also Leippold and Yu (2023) show that firms that engage in green innovation reduce carbon emissions over time. El-Bannan and Löffler (2024) document a significantly negative relationship between the volume of issued green bonds and future carbon intensity. This effect is concentrated among financially constrained firms, highlighting that the issuance of green bonds relaxes financial constraints, which enhances green innovations by issuing firms.

On the contrary, Bolton et al. (2023) find that there is path-dependency in innovation, as green innovation is predominantly undertaken by firms that are already green, while brown firms tend to innovate in brown technologies.Consequently,they find that green innovation does not reduce carbon emissions. This is confirmed by Dugoua and Gerarden (2023). Also Hartzmark and Shue (2023) demonstrate that brown firms face weak incentives to become more green, indicating that directing capital away from brown firms and toward green firms may be counterproductive as it makes brown firms more brown without making green firms more green.

Following Bolton et al. (2023), we estimate the impact of green innovation on corporate environmental performance by linking a companies' future emission intensity to its contemporaneous green innovation activity. That is, we estimate the following regression at the firm-year level:

$$\text{Environ. Performance}_{f,t} = \beta \text{Green Patent}_{f,t-h} + \delta' X_{f,t-1} + \eta_f + \lambda_t + \upsilon_{f,t} \qquad (4.10.5)$$

where we use emission intensity as our main measure of environmental performance. We also verify the robustness of the results against using the absolute Scope 1 and 2 emissions (in log) as measure of environmental performance. We use either the green patent ratio as main explanatory variable in Equation (4.10.5) or the amount of green patents (in log). We include the vector of corporate fundamentals ($X_{f,t}$) and incorpo-

rate firm- (η_f) and time-fixed effects (λ_t).[61] For the regressions with absolute scope 1 and 2 emissions as dependent variable, we additionally include revenue (in log) as control variable. We estimate the effect over a horizon of one-, two- and three-years, i.e., $h \in \{1, 2, 3\}$. As before, standard errors are clustered at the industry-level. In each specification, Column 1-3 report the results when considering the green patent ratio as explanatory variable, and Column 4-6 report the results when using the (log) number of green patents as explanatory variable.

4.10.1 Emission Intensity

Following Bolton et al. (2023), we estimate the impact of green innovation on corporate environmental performance by linking a companies' future emission intensity to its contemporaneous green innovation activity. We fail to find evidence that an increase in the amount of green patents leads to lower emission intensity. The estimates in Column 1-3 indicate that the green patent ratio is positively associated with a company's future emission intensity. However, the relationship is statistically insignificant at the one- and two- and three-year horizon for the green patent ratio. We find comparable results when considering the number of green patents as explanatory variable. In this case, we find a statistically significant, yet positive, relationship between emissions intensity and the green patent ratio at the two-year horizon.

[61] Note that firm-fixed effects control for the average emission intensity of a given company over the sample period.

Table 4.10.27: Linking Green Innovation and Environmental Performance

	Emission Intensity$_{f,t}$					
VARIABLES	(1)	(2)	(3)	(4)	(5)	(6)
Green Patent Ratio$_{f,t-1}$	25.626					
	(15.558)					
Green Patent Ratio$_{f,t-2}$		21.842				
		(30.524)				
Green Patent Ratio$_{f,t-3}$			22.051			
			(43.398)			
Green Patents$_{f,t-1}$				0.311		
				(0.227)		
Green Patents$_{f,t-2}$					0.669*	
					(0.385)	
Green Patents$_{f,t-3}$						0.035
						(0.533)
Corporate Fundamentals	Yes	Yes	Yes	Yes	Yes	Yes
Time-FEs	Yes	Yes	Yes	Yes	Yes	Yes
Firm-FEs	Yes	Yes	Yes	Yes	Yes	Yes
Observations	1,408	1,038	728	1,307	957	666
R-squared	0.952	0.952	0.967	0.961	0.963	0.979

*Note: OLS estimation results of Equation 4.10.5 with firm- and time fixed effects. We estimate the relationship between emission intensity, measured in CO2e/USDm, and the green patent ratio using a 1-, 2- and 3-year lag of the green patent ratio (column 1-3), and the amount of green patents measured in natural logarithms (column 4-6). We include a set of corporate fundamentals, i.e., the profitability-ratio, leverage-ratio, cash-ratio, and investment-ratio. Standard errors are reported in parentheses errors and are clustered at the industry-level. *** p<0.01, ** p<0.05, * p<0.1.*

4.10.2 Absolute Scope 1 and 2 Emissions

We verify the robustness of our results using absolute scope 1 and 2 emission levels as outcome variable in Table 4.10.28. Again, we find no evidence that the green patent ratio or the number of green patents is associated with absolute scope 1 and 2 emissions, at the horizons we consider.

Table 4.10.28: Linking Green Patenting to Environmental Performance

	Absolute Scope 1 and 2 Emissions$_{f,t}$					
	(1)	(2)	(3)	(4)	(5)	(6)
Green Patent Ratio$_{f,t-1}$	3.724					
	(3.225)					
Green Patent Ratio$_{f,t-2}$		-2.114				
		(3.283)				
Green Patent Ratio$_{f,t-3}$			4.627			
			(8.962)			
Green Patents$_{f,t-1}$				0.127		
				(0.095)		
Green Patents$_{f,t-2}$					0.125	
					(0.135)	
Green Patents$_{f,t-3}$						0.078
						(0.159)
Corporate Fundamentals	Yes	Yes	Yes	Yes	Yes	Yes
Time-FEs	Yes	Yes	Yes	Yes	Yes	Yes
Firm-FEs	Yes	Yes	Yes	Yes	Yes	Yes
Observations	1,442	1,062	743	1,331	974	676
R-squared	0.962	0.961	0.962	0.968	0.969	0.971

*Note: Robustness tests for Equation (3), estimated by OLS including firm- and time fixed effects. We estimate the relationship between the natural logarithm of absolute scope 1 and 2 emissions, measured in CO2e, and the green patent ratio using a 1-, 2- and 3-year lag of the green patent ratio (column 1-3), and the amount of green patents measured in natural logarithms (column 4-6). We include a set of corporate fundamentals, i.e., the profitability-ratio, leverage-ratio, cash-ratio, investment-ratio, and the natural logarithm of revenue. Standard errors are reported in parentheses errors and are clustered at the industry-level. *** p<0.01, ** p<0.05, * p<0.1.*

4.10.3 GMM

Though we control for firm specific effects and exploit lagged green patent activity, there may still be reverse causality issues leading to bias in the fixed effects OLS estimator. This is because emission-intensive firms may have more incentives to innovate in the green space. We therefore also estimate the relationship using the Arellano and Bond (1991) two-step GMM estimator. The results using emission intensity as outcome variable are reported in Table 4.10.29 and the results using absolute scope 1 and 2 emissions are reported in Table 4.10.30. This procedure does not provide conclusive evidence either. We find a statistically significant and positive relationship between emission intensity and the number of green patents at the three-year horizon. This association remains present when considering the absolute scope 1 and 2 emission levels.

Table 4.10.29: Linking Green Patenting to Environmental Performance

	Emission Intensity$_{f,t}$					
	(1)	(2)	(3)	(4)	(5)	(6)
Green Patent Ratio$_{f,t-1}$	32.6711					
	(64.219)					
Green Patent Ratio$_{f,t-2}$		38.4620				
		(105.731)				
Green Patent Ratio$_{f,t-3}$			242.1941***			
			(60.103)			
Green Patents$_{f,t-1}$				-0.7680		
				(0.474)		
Green Patents$_{f,t-2}$					-0.6462	
					(0.774)	
Green Patents$_{f,t-3}$						2.1431
						(3.045)
Corporate Fundamentals	Yes	Yes	Yes	Yes	Yes	Yes
Time-FEs	Yes	Yes	Yes	Yes	Yes	Yes
Hansen p-value	0.167	0.255	0.270	0.901	0.869	0.821
AR(1) p-value	0.239	0.217	0.401	0.539	0.419	0.632
AR(2) p-value	0.041	0.842	-	0.046	0.206	-
Observations	1,408	1,038	728	1,307	957	666

*Note: Robustness tests for Equation (3), estimated by GMM with time fixed effects. We estimate the relationship between emission intensity, measured in CO2e/USDm, and the green patent ratio using a 1-, 2- and 3-year lag of the green patent ratio (column 1-3), and the amount of green patents measured in natural logarithms (column 4-6). We include a set of corporate fundamentals, i.e., the profitability-ratio, leverage-ratio, cash-ratio, and investment-ratio. Standard errors are reported in parentheses errors and are clustered at the industry-level. *** p<0.01, ** p<0.05, * p<0.1.*

Table 4.10.30: Linking Green Patenting to Environmental Performance

	Absolute Scope 1 and 2 Emissions$_{f,t}$					
VARIABLES	(1)	(2)	(3)	(4)	(5)	(6)
Green Patent Ratio$_{f,t-1}$	10.5192*					
	(5.721)					
Green Patent Ratio$_{f,t-2}$		4.8072				
		(12.211)				
Green Patent Ratio$_{f,t-3}$			61.7753**			
			(26.995)			
Green Patents$_{f,t-1}$				-0.1648		
				(0.223)		
Green Patents$_{f,t-2}$					0.7751	
					(0.617)	
Green Patents$_{f,t-3}$						1.5360
						(2.125)
Corporate Fundamentals	Yes	Yes	Yes	Yes	Yes	Yes
Time-FEs	Yes	Yes	Yes	Yes	Yes	Yes
Hansen p-value	0.358	0.523	0.281	0.161	0.479	0.166
AR(1) p-value	0.096	0.119	0.116	0.129	0.149	0.215
AR(2) p-value	0.268	0.774	-	0.486	0.621	-
Observations	1,442	1,062	743	1,331	974	676

*Note: Robustness tests for Equation (3), estimated by GMM with time fixed effects. We estimate the relationship between the natural logarithm of the absolute scope 1 and 2 emissions, measured in CO2e, and the green patent ratio using a 1-, 2- and 3-year lag of the green patent ratio (column 1-3), and the amount of green patents measured in natural logarithms (column 4-6). We include a set of corporate fundamentals, i.e., the profitability-ratio, leverage-ratio, cash-ratio, investment-ratio, and the natural logarithm of revenue. Standard errors are reported in parentheses errors and are clustered at the industry-level. *** p<0.01, ** p<0.05, * p<0.1.*

In this case, we also find a statistically significant and positive relationship between absolute scope 1 and 2 emissions and the green patent ratio at the one-year horizon.

Overall, our results do not provide a clear answer to whether green innovation improves environmental performance. This is qualitatively in line with Bolton et al. (2023), who do not find that green innovation materializes into future emission reductions. This raises the question why investors take green innovation into account in the bond pricing relationship. One explanation is that investors anticipate emission reductions over a longer horizon. While our data does not show that green innovation leads to emission reductions within one, two, or even three years, it is possible that implementing patented green technologies and achieving the associated emission reductions takes longer. However, extending the time frame makes it more challenging

to clearly identify the effect of green innovation on corporate environmental performance. While we are not able to test this in our data, another potential explanation is that owning green patents signals to investors that the company possesses advanced green technologies. This has a positive option value, especially if investors anticipate stricter climate policies in the future, since it positions the firm to respond more effectively to increased policy stringency. Our results may suggest that investors take this option value into consideration in their investment decisions.

4.11 Holder-Dynamics

4.11.1 Evolution of the Holder-Shares

Table 4.11.31: Evolution of (Unscaled) Shares

Period	EU	Inst.	Insur.	Mfund	Pfund	Bank
2016-Q2	0.374	0.314	0.172	0.144	0.012	0.035
2016-Q3	0.373	0.316	0.170	0.148	0.012	0.034
2016-Q4	0.369	0.311	0.170	0.141	0.012	0.034
2017-Q1	0.370	0.317	0.174	0.144	0.014	0.035
2017-Q2	0.364	0.311	0.170	0.141	0.013	0.035
2017-Q3	0.360	0.308	0.167	0.141	0.013	0.036
2017-Q4	0.352	0.302	0.159	0.144	0.013	0.033
2018-Q1	0.346	0.299	0.159	0.140	0.013	0.032
2018-Q2	0.336	0.288	0.147	0.139	0.013	0.032
2018-Q3	0.338	0.291	0.150	0.139	0.012	0.032
2018-Q4	0.333	0.285	0.150	0.134	0.012	0.034
2019-Q1	0.333	0.286	0.146	0.136	0.012	0.033
2019-Q2	0.348	0.300	0.153	0.143	0.013	0.035
2019-Q3	0.345	0.296	0.149	0.144	0.013	0.035
2019-Q4	0.341	0.295	0.150	0.142	0.014	0.035
2020-Q1	0.317	0.273	0.138	0.130	0.013	0.031
2020-Q2	0.329	0.284	0.143	0.135	0.014	0.032
2020-Q3	0.323	0.282	0.136	0.139	0.014	0.030
2020-Q4	0.322	0.282	0.136	0.145	0.020	0.033
2021q1	0.318	0.277	0.134	0.139	0.018	0.032
2021-Q2	0.313	0.273	0.135	0.135	0.018	0.032
2021-Q3	0.307	0.267	0.131	0.133	0.018	0.033
2021-Q4	0.303	0.264	0.129	0.131	0.018	0.032
Total	0.338	0.291	0.149	0.139	0.014	0.033

Note: Based on a sample of 39,046 observations, reported at the quarterly frequency and bond level. We distinguish between EU-holders, institutional investors (insurance companies, mutual funds, pension funds), and banks. The unscaled holder-share is defined as the holdings of a specific European investor sector of a given bond relative to the total amount outstanding (at market values) in a given period.

Table 4.11.32: Evolution of (Scaled) Shares

Period	EU	Inst.	Insur.	Mfund	Pfund	Bank
2016-Q2	0.374	0.347	0.285	0.273	0.228	0.261
2016-Q3	0.373	0.347	0.283	0.277	0.231	0.263
2016-Q4	0.369	0.342	0.287	0.265	0.231	0.264
2017-Q1	0.370	0.349	0.295	0.264	0.231	0.261
2017-Q2	0.364	0.342	0.294	0.259	0.232	0.263
2017-Q3	0.360	0.339	0.290	0.256	0.233	0.263
2017-Q3	0.352	0.333	0.280	0.256	0.231	0.259
2018-Q1	0.346	0.329	0.278	0.249	0.228	0.258
2018-Q2	0.336	0.318	0.270	0.250	0.230	0.261
2018-Q3	0.338	0.321	0.274	0.248	0.233	0.259
2018-Q4	0.333	0.315	0.269	0.241	0.227	0.262
2019-Q1	0.333	0.316	0.269	0.245	0.233	0.257
2019-Q2	0.348	0.330	0.280	0.256	0.241	0.272
2019-Q3	0.345	0.326	0.276	0.254	0.240	0.272
2019-Q4	0.341	0.323	0.281	0.246	0.241	0.272
2020-Q1	0.317	0.302	0.268	0.233	0.221	0.253
2020-Q2	0.329	0.312	0.279	0.240	0.234	0.262
2020-Q3	0.323	0.310	0.274	0.245	0.240	0.265
2020-Q4	0.322	0.310	0.276	0.252	0.248	0.266
2021-Q1	0.318	0.305	0.271	0.243	0.243	0.258
2021-Q2	0.313	0.301	0.274	0.235	0.241	0.259
2021-Q3	0.307	0.294	0.271	0.231	0.242	0.262
2021-Q4	0.303	0.291	0.270	0.230	0.223	0.260
Total	0.338	0.320	0.278	0.249	0.234	0.262

Note: Based on a sample of 39,046 observations, reported at the quarterly frequency and bond level. We distinguish between EU-holders, institutional investors (insurance companies, mutual funds, pension funds), and banks. The scaled holder-share is equal to the unscaled holder share scaled by the relative size of the investor sector. The unscaled holder-share is defined as the holdings of a specific European investor sector of a given bond relative to the total amount outstanding (at market values) in a given period.

4.11.2 Summary Statistics of the Stock Regressions

Table 4.11.33: Summary statistics

	Mean	Median	SD	P10	P90
Stock Return (in %)	0.531	0.733	8.543	-8.149	9.382
Market Capitalization (in bEUR)	42.967	13.699	125.272	1.600	92.613
RoE	11.467	9.903	43.923	-5.374	30.290
Book to Market	0.610	0.484	0.538	0.114	1.207
Leverage-Ratio (%)	29.036	27.637	12.861	13.856	46.520
Investment-Ratio (%)	7.382	2.692	23.537	-11.211	28.006
PPE (in log)	8.437	8.558	1.714	6.147	10.615
Sales growth (%)	6.810	3.383	36.475	-14.704	28.705
EPS-growth (%)	0.285	0.253	19.554	-8.580	8.102
Beta	1.016	0.997	0.406	0.496	1.559
Volatility	0.075	0.063	0.043	0.034	0.130
Climate Innovations	0.089	0.013	0.375	-0.255	0.651

Note: Based on 11,611 observations, reported at monthly frequency and the firm-level. Stock returns is winsorized at the 99th percentile. The RoE is defined as net income divided by shareholders' equity. The book-to-market ratio is defined as (book value per share times shares outstanding) divided by (market price per share times shares outstanding). The leverage ratio is defined as total debt over total assets. The investment ratio is defined as the year-over-year growth rate of tangible assets, and is winsorized at 2.5 percent. PPE is defined as tangible assets. Sales growth is defined as the year-over-year growth rate of the firm's revenue. EPS growth is defined as the annual change in the firm's EPS normalized by the firm's stock price. The market beta is defined as the CAPM beta calculated over a 12-month period using daily data. The volatility of the firm's stock is defined as the standard deviation of stock returns based on the past 12 months of monthly returns. All ratio's are reported in percentages.

Table 4.11.34: Summary statistics of Climate Beta

	Mean	Median	SD	P10	P90
Climate Beta	0.041	0.028	0.541	-0.101	0.162

Note: Based on 2,376 observations, reported at quarterly frequency and the firm-level. Climate Beta is the firm exposure to climate risk.

Chapter 5

Home Improvement, Wealth Inequality, and the Energy-Efficiency Paradox[1]

Abstract

This chapter explores the pace at which households transition to greener housing and its effects on the distribution of wealth and CO2 emissions. Using unique Dutch data, we document that lower-income households are less likely to undertake energy-efficiency improvements, while higher-income households are more likely to sort into energy-efficient homes. Energy savings represent 17% of median net wealth, with sorting accounting for 65% of this effect. Policies encouraging green housing among lower-income households reduce poverty and wealth inequality, but only realize 37% of the potential CO2 emission reduction. Our findings highlight a fundamental trade-off between advancing climate goals and promoting redistribution.

Keywords: Energy efficiency, wealth inequality, CO2 emissions.

JEL codes: D31, Q41, R31.

[1] This chapter is based on Dröes & Van der Straten (2024). Tinbergen Institute Discussion Paper No. TI 2024-026/IV.

5.1 Introduction

Given climate goals and the significant share of greenhouse gas emissions attributable to households, improving the energy efficiency of the housing stock has become a key priority for policymakers. While there is a growing body of research on the effectiveness of government-led home improvement programs (Fowlie, Greenstone, and Wolfram, 2018) and stricter building codes (e.g. Aroonruengsawat, Auffhammer, and Sanstad, 2012; Jacobsen and Kotchen, 2013), the capitalization of energy labels in house prices (e.g. Brounen and Kok, 2011; Fuerst, McAllister, Nanda, and Wyatt, 2016; Kahn and Kok, 2014) and the returns on home improvements (e.g. Kattenberg, Eichholtz, and Kok, 2023; Metcalf and Hassett, 1999), much less is known about the underlying distribution of energy efficiency across households. In particular, to what extent do households with higher income and wealth shield themselves from rising energy costs by adopting energy efficiency enhancements in their homes? And how do public policies aimed at greening the housing stock affect both the accumulation and distribution of wealth, as well as aggregate CO2 emission reductions?

This paper shows that income and wealth play a central role in shaping households' ability to invest in energy efficiency, resulting in significant differences in the pace at which different households transition to greener housing. We examine two distinct margins: the intensive margin, referring to households undertaking energy-efficiency enhancing home improvements, and the extensive margin, capturing how households sort into more energy-efficient homes. Our analysis covers the full spectrum of the housing market—owner-occupied, private rental, and social housing.[2] We also study how these differences in becoming green affect both the accumulation and distribution of wealth, and the distribution of potential CO2 emission reductions. In particular,

[2] Many existing policies focus primarily on the intensive margin, and prior research often examines either the intensive or extensive margin, typically within a single housing sector. Yet, lower-income households are more likely to live in social housing, while higher-income households tend to reside in rental or owner-occupied homes. The incentives to invest in energy efficiency differ across these sectors, and the intensive margin alone captures only part of households' efforts to go green. To fully understand which households invest in energy efficiency and how this affects the distribution of energy expenditures and CO2 emissions, it is essential to consider both margins across all housing sectors and income levels.

we assess the implications of policies that aim to shelter low-income households from rising energy costs. We find that such policies may have limited impact on aggregate CO2 emission reductions because lower-income households typically have a smaller carbon footprint. Our findings point to a fundamental trade-off between climate goals and redistribution: reducing poverty and inequality does not necessarily align with achieving the largest CO2 emission reductions, which are concentrated among higher-income households.

We use a unique dataset from the Netherlands that combines survey information on whether households have undertaken home improvements and the types of improvements made. The survey data is linked to administrative data on energy efficiency, energy expenditures, and tax registry data on disposable household income and (net) wealth. Specifically, the data come from the Dutch Housing Demand Survey (WoON) of 2018, which includes approximately 55,000 respondents across owner-occupied housing, as well as the private and social rental markets. We find that a one percent increase in disposable household income raises the probability of making home improvements by 7 percent- an economically significant effect given the average probability of 57 percent. This effect is mainly driven by households in the owner-occupied market segment, as households in the rental sector must rely on the owner of the house to undertake home improvements. The effect of an increase in income is largest on the probability of installing a boiler and insulating the home. The effect is smallest for the propensity to install solar panels. This suggests that, as income rises, households tend to prioritize home improvements that yield the largest energy efficiency gains. A one percent increase in household income increases the likelihood of residing in an energy-efficient home by 5.8 percent. We find similar qualitative patterns across different tenure types, though the relationship is quantitatively weaker in the rental sector—particularly in the private rental market—suggesting that supply constraints may limit households' ability to move into more energy-efficient housing.

Our survey data also provides information about the reasons that households chose to undertake (or abstain from undertaking) energy efficiency enhancing home improve-

ments. This information is particularly relevant for understanding the underlying motivations behind energy efficiency investments, especially given prior evidence suggesting that their returns may be negative (e.g., Fowlie et al., 2018). Among the respondents that did undertake energy efficiency enhancements in their home, approximately half reported that these improvements were necessary due to maintenance. A quarter of respondents believed the investment would pay off financially, while a fifth did home improvements to make their home more comfortable. Among the respondents that did not undertake energy efficiency enhancements in their home, the most common reason was that their home was already energy efficient. Financial constraints were also mentioned often, with a substantial share of households indicating that home improvements were outside their budget, or that they lacked sufficient savings. Looking ahead, the survey also asked households under what conditions they would consider undertaking (additional) home improvements. Among those willing to make energy efficiency enhancements in the future, one fifth reported they would do so even if the net present value were negative. This suggests that a non-negligible share of households is be motivated by non-financial factors when making home improvement decisions and these households tend to have higher incomes. This pattern is not consistent with a purely financial literacy explanation, where higher-income households better recognize and capitalize on returns, but rather indicates that green preferences likely play an important role.

We also assess the role of subsidies in encouraging energy efficiency investments. The Netherlands has introduced a large-scale subsidy program aimed at supporting energy efficiency measures, with the goal of lowering financial barriers. We find that subsidy uptake varies by the type of home improvement undertaken. Crucially, uptake increases monotonically with income across all improvement types, suggesting that subsidies primarily benefit higher-income households – those who generally rely less on financial support to undertake energy efficiency enhancements. We further examine whether households are more likely to use wealth, rather than income, to invest in energy efficiency-enhancing home improvements or the purchase a more energy-

efficient home. Although our results indicate that wealth has a positive and statistically significant effect on both outcomes, we find that the magnitude of the effect is notably larger for income than for wealth, suggesting that liquid financial resources are more important in determining households' decisions to invest in energy efficiency than their accumulated assets.

The average annual reduction in utility expenditures resulting from energy efficiency enhancing home improvements and residing in an energy-efficient home amounts to 26 percent of the average total utility expenditures. The present value of the expected savings amounts to 17 percent of the median net wealth, with sorting explaining 65 percent of these savings. While government support often focuses on subsidizing energy-efficiency enhancing home improvements, our findings suggest that public policy should also prioritize encouraging households to purchase energy-efficient homes, for instance by promoting green mortgages or implementing stricter building codes.

We explore the effect of energy efficiency investments on the distribution of (net) wealth and poverty, showing that the investments undertaken reduce in wealth inequality and poverty within society. Although high-income households are more likely to undertake energy-efficiency-enhancing home improvements, this effect is offset by the disproportionately larger gains, relative to their wealth, that lower-income households experience from living in an energy-efficient home. Importantly, these energy savings are highly unequal: for households in the lowest income quartile, the savings correspond to 36 percent of median net wealth, compared to just 7 percent for those in the highest quartile. In contrast, the CO2 emissions from residential energy use are 1.5 times higher for households in the top income quartile, and nearly half of the unrealized CO2 emission reduction potential is concentrated among these households. This brings forward a policy trade-off between reducing poverty and inequality related to energy efficiency versus effectively reducing CO2 emissions. A policy that makes the home of below-median income households green would reduce poverty by 1.3 percentage points, but this would leave 63 percent of potential CO2 emission reductions unrealized. Focusing solely on the first quartile of households leaves 83 reductions of

the reduction potential unrealized. Paradoxically, achieving climate goals therefore requires incentivizing those households that emit the most CO2, which are high-income households, rather than focusing on those that are economically hurt most from rising energy costs.

Our paper contributes to a growing body of literature on energy efficiency investments. Fowlie et al. (2018) estimate the returns on investments in energy efficiency made under the Michigan weatherization program. They find that the returns on these investments are negative. Fowlie et al. (2018) show that this cannot be attributed to an increase in energy demand due to improved efficiency (i.e., a "rebound effect") and show that returns remain negative when broader societal benefits are taken into account. The experience in the Netherlands has been different, with some reporting a positive return on home insulation (Kattenberg et al., 2023).[3] Hancevic and Sandoval (2022) also study the effect of housing investments on energy consumption, documenting that such investments reduce electricity use, but have no effect on natural gas use. Instead, using data from Gainesville, Florida, Jacobsen and Kotchen (2013) show that building codes are effective in reducing both electricity and natural gas consumption.

Our paper is also related to Roberdel, Ossokina, Karamychev, and Arentze (2023), who study low-income households in the social housing sector and use a quasi-experimental design to show that the effect of a Dutch policy aimed at improving the energy efficiency of houses leads to a significantly smaller reduction in energy use for those in the very left tail of the income distribution. Ossokina, Kerperien, and Arentze (2021) show that public housing tenants in the Netherlands require a 30 percent return on the retrofit of their home and are more likely to do home improvements if they get the right information. Using Danish inheritance data, Berg, Nielsson, and Streitz (2024) find that shocks to wealth has a positive effect on installing green heating, with the effect being

[3] Kattenberg et al. (2023) find that home insulation reduces gas consumption by approximately 20 percent, on average, for both owner-occupied and rental homes, and find no evidence of a rebound effect. In contrast, Aydin, Kok, and Brounen (2017) do find evidence of a rebound effect based on energy performance certificates (EPC) and using a Dutch household panel dataset.

largest for the lower part of the wealth distribution.[4]

The key contribution of this article compared to the aforementioned studies is that we examine distribution of energy efficiency across household, and how this affects the accumulation and distribution of wealth and CO2 emission reductions. Although there is a long line of research on wealth inequality (for an overview, see Benhabib, Bisin, and Luo, 2019) that focuses on the decomposition of inequality based on savings and income, less research has been done on the impact of the green energy transition on the accumulation and distribution of wealth.[5] Related, Fried (2024) assesses the distributional impacts of higher temperatures in the US, by quantifying a macro heterogeneous-agent model in which households are heterogeneous in terms of their income, as well as their ability to specialize in different types of heating equipment. The author finds that the welfare effects of climate change vary considerably by income and region. Kuhn and Schlattmann (2024) develop a life-cycle model incorporating heterogeneous adoption rates of clean goods across income groups to quantify carbon reductions resulting from various carbon taxes and subsidies. Their findings show that such policies primarily accelerate emissions reductions by incentivizing high-income households, who are the largest emitters. However, this has redistributional effects due to net transfers from low- to high-income groups. Instead, our paper provides empirical evidence that high-income households are more likely to invest in energy efficiency improvements in their homes, leading to redistributional effects through energy savings. We demonstrate that this pattern arises precisely because energy savings are unevenly distributed across households with varying income profiles. While our results on which households emit the most aligns with Kuhn and Schlattmann (2024), the focus of our paper and the trade-offs we explore are fundamentally different.

[4] Our paper further relates to Potepan (1989), who studies income dynamics for 1979. The author argues that homeowners tend to upgrade their current home rather than moving to a new one when interest rates are higher or when technological constraints are slack. While also examining the the extensive and intensive margin, Potepan (1989), does not focus on energy efficiency.

[5] Our paper builds on the theoretical work of Van der Straten (2023), who shows that credit constrained households have weaker incentives to adapt to climate change. This has redistributive implications, as these households fail to optimally reduce their vulnerability to climate impacts, and thus lose a relatively larger fraction of their housing wealth upon the realization of an extreme weather event.

The remainder of this paper is structured as follows. In Section 5.2, we show a household-level conceptual framework that highlights key choices and trade-offs of energy efficiency. In Section 5.4, we introduce the data. The results are presented in Section 5.5 and 5.6. We explore policy counterfactuals in 5.7. Section 5.8 concludes.

5.2 Conceptual framework

The purpose of this section is to illustrate the choice for energy-efficiency enhancing home improvements and to discuss how these affects CO2 emissions and energy savings. Households live for two periods. In the first period, they allocate income to the purchase of housing capital H_t (with a relative price p) and invest in energy efficiency. Any remaining income is saved. In the second period, households purchase energy e_{t+1} (per unit of housing capital, at a relative price q), which is used within the home. Housing is sold again at the end of the second period, and any remaining resources are spent on a non-durable consumption good c_{t+1} (with a price normalized to 1). Households derive utility only in the second period, from consumption, energy services, and the housing capital stock accumulated in the first period.[6] Preferences are represented by the following nested CES utility function:

$$U\left(c_{i,t+1}, e_{i,t+1}, H_{i,t+1}\right) = \left[\theta\left(H_{i,t+1}^{\rho} \cdot e_{i,t+1}^{1-\rho}\right)^{\eta} + (1-\theta)c_{i,t+1}^{\eta}\right]^{1/\eta} \tag{5.2.1}$$

with $\theta > 0$ the relative importance of housing-energy consumption relative to non-durable consumption, $\rho > 0$ the substitution between housing and energy and $\eta < 0$ the elasticity of substitution between housing services and consumption.[7]

Household i invests in energy efficiency, $x_{i,t}$, at time t when purchasing their housing

[6] For simplicity, we assume that housing is a durable good which does not depreciate, i.e., $H_{i,t+1} = H_{i,t}$.

[7] A negative elasticity of substitution between housing services and consumption implies that these good (bundles) are imperfect substitutes. Specifically, there is some soft complementarity, meaning that non-durable consumption still provides utility without housing — but its marginal utility is limited unless one also consumes housing services. For the model simulation, we focus on the case where substitution between housing and energy (ρ) is low, meaning these inputs are complements. That is, households do not obtain any utility from consuming housing without consuming energy.

capital, with $x_{i,t} \in [0, 1)$ (cf. Van der Straten (2023)). The investment in energy efficiency can be viewed as (i) the premium paid to purchase of a more energy efficient home (extensive margin), or as (ii) the investment required for making home improvements (intensive margin). By investing in energy efficiency, the amount of energy, $e_{i,t+1}$, consumed per unit of housing capital, $H_{i,t}$, decreases by a factor, $x_{i,t}^{\phi}$, where $\phi < 1$ is a parameter that governs the returns to energy efficiency enhancements.[8] This reduces energy costs:

$$C_{i,t+1}^{e}(e_{i,t+1}, H_{i,t}, x_{i,t}) = (1 - \underbrace{x_{i,t}^{\phi}) \cdot e_{i,t+1} \cdot q}_{S_{i,t+1}} \cdot H_{i,t} \tag{5.2.2}$$

where $S_{i,t+1}$ denote the savings in energy costs per unit of housing for household i in period $t + 1$. Investing in energy efficiency is costly, however. The costs of reaching a higher level of energy efficiency rise at an accelerating rate as energy efficiency increases. Furthermore, the costs of acquiring energy efficiency increase in the units of housing owned, as the costs of, for example, insulation rise in the size (in m^2) of the home:

$$C_{i,t}^{x}(H_{i,t}, x_{i,t}) = \frac{1}{2} H_{i,t} \cdot (x_{i,t})^2 \tag{5.2.3}$$

Households have heterogeneous (and exogenous) income and wealth profiles. The income of household i in period t is denoted by $y_{i,t}$ and household i is endowed with an initial wealth of $A_{i,0} = v(y_{i,t})$ where $v' > 0, v'' < 0$. Households only earn income in the first period, but can save part of their income (and wealth) for future consumption. On these savings, households earn a rate of return of r, which is exogenously given. Define $A_{i,t}^{net}$ as the net savings of a household i in period t:

$$A_{i,t}^{net}(H_{i,t}, x_{i,t}) = (y_i + A_{i,0}) - \left(p + \frac{1}{2} x_{i,t}^2 \right) \cdot H_{i,t} \tag{5.2.4}$$

[8] A value of $\phi < 1$ implies diminishing returns to energy efficiency enhancements, meaning that the marginal energy savings from additional efficiency investments decrease.

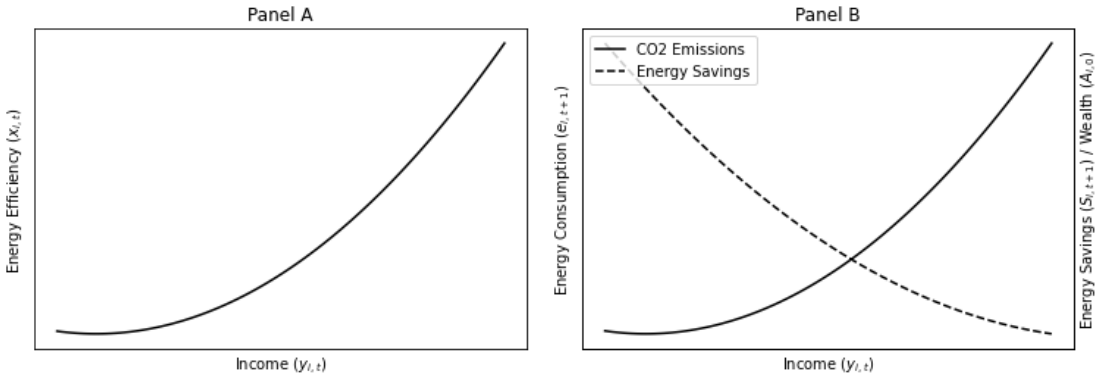


Figure 5.2.1: Intensive, extensive margin and trade-off emissions and savings

Note: Panel A shows the optimal choice of energy-efficiency (x_t). Panel B shows the optimal demand for energy (e_{t+1}), representing CO2 emissions, and the energy costs savings relative to initial wealth (S_{t+1}/A_0).

The solution to the household utility optimization problem can be found in Appendix A1. The model illustrates the two key points that are explored in this paper in Panel A and, respectively, Panel B, depicted in Figure 5.2.1. Panel A illustrates that households with higher incomes invest more in improving the energy efficiency of their homes. Nevertheless, this does not lead to a reduction in energy consumption, as the demand for energy, and therefore CO2 emissions rises with income. This is shown in Panel B.[9] Panel B also shows that energy savings relative to wealth decrease as income rises.[10] Although higher-income households demand more energy efficiency, the energy savings associated with energy efficiency improvements are therefore of greater significance for low-income households relative to their wealth. Instead, the potential reduction in CO2 emissions is greater for high-income households, as they emit the most CO2. We explore these differences in undertaking energy efficiency enhancing home improvements based on income (Panel A) and their effect on energy savings (wealth accumulation) versus CO2 benefits (Panel B) empirically.

[9] For simplicity, we assume that the consumption of housing and the non-durable consumption good do not generate emissions on their own. Moreover, we do not differentiate between different types of energy and their emission intensity.

[10] Note that the energy savings per unit of housing decline with housing size, implying that the marginal value of additional energy-efficiency investment decreases per unit of housing. This reflects diminishing per-unit returns to energy efficiency improvements as homes become larger.

5.3 Institutional context

Households in the Netherlands accounted for 21 percent of greenhouse gas emissions in 2018 (CBS, 2018). While this is lower than the global household average, reducing emissions – especially those tied to residential energy use – has been a core focus of Dutch climate policy. As a member of the European Union, the Netherlands operates within the broader EU climate framework, meaning its policies on energy efficiency in housing are largely shaped by EU directives and are representative of institutional efforts across member states.[11]

In 2009, the EU introduced the Renewable Energy Directive, requiring member states to collectively raise renewable energy's share to 20 percent by 2020. The Netherlands committed to a national target of 14 percent, formalized in the 2013 Energy Agreement, which was endorsed by a wide coalition of societal stakeholders, including labor unions, environmental organizations, and financial institutions. In parallel, the 2010 recast of the Energy Performance of Buildings Directive (EPBD) introduced stricter building standards. It mandated energy performance certificates (EPCs) in property listings, set minimum efficiency standards for new construction and major renovations, and required all new buildings to be nearly zero-energy by the end of 2020. Anticipating these changes, the Netherlands had already implemented a national energy labeling scheme, ranging from label A (most efficient) to G (least efficient). Building on the Energy Agreement, the 2019 National Climate Agreement committed to reducing CO2 emissions by 49 percent by 2030 (relative to 1990 levels) and by 95 percent by 2050. Housing plays a central role in this strategy. The agreement calls for retrofitting 1.5 million existing homes by 2030, including insulation upgrades, renewable heating, and better integration of clean energy sources. To support this, the government introduced large-scale financial support programs.

The most prominent scheme is the "Investeringssubsidie Duurzame Energie (ISDE)", launched in 2016 to subsidize renewable heating technologies such as heat pumps,

[11] This lends broader external validity to the Dutch case in understanding household energy transitions across the EU.

solar water heaters, and biomass boilers.[12] Solar energy uptake has also been incentivized. Since 2004, households installing solar panels have benefited from a net metering scheme, enabling them to offset electricity bills by supplying excess energy back to the grid. In addition, homeowners installing panels after mid-2013 could claim a VAT refund, and as of 2023, the VAT on solar panels has been reduced to zero. Homeowners are also encouraged to obtain an energy savings loan. This is a low-interest loan intended to support energy efficiency improvements. These loans have been available since 2014 through the National Energy Savings Fund, which is publicly and privately financed. The fund offers terms ranging from 10 to 20 years, with fixed interest rates over the duration of the loan.[13]

5.4 Data and descriptive statistics

Our main data source is the Dutch Housing Demand Survey (WoON), which has been conducted on behalf of the Dutch government for several decades. The survey supports the policy making of the Dutch government. We use the Housing Market module of the WoON-survey (other modules are, e.g., recording residential environment, home improvement and home maintenance, energy and security, livability, consumer behavior and affordability, housing and care, structural home inspection). The Housing Market module takes place once every three years and surveys roughly 40,000 individuals. Each wave is dedicated to a specific topic. We use the 2018 waves of the survey, which was dedicated to the topic energy use in the house.[14] There are 67,523 to the 2018 wave

[12] This scheme was previously known as the Subsidie Energiebesparing Eigen Huis (SEEH). For the rental sector, the Stimuleringsregeling aardgasvrije huurwoningen (SAH) encourages landlords to disconnect properties from the gas grid and switch to district heating.

[13] Since mid-2021, the program has been expanded to offer financing to homeowners who lack borrowing capacity or do not qualify due to age.

[14] The 2018 wave was the first wave that includes proxies for both home improvements and energy efficiency, as well as administrative information on (net) wealth. A later survey, which includes proxies for home improvements and energy efficiency, was conducted during the COVID-19 pandemic that began in the Netherlands in February 2020. Due to a major lockdown, the sampling period was split into two parts and the response rate was lower. Moreover, households faced other challenges during this period, making home improvements or purchasing energy-efficient housing less of a priority. As a result, 2021 is not the most representative year for examining this topic. Therefore, we will not use the 2021 sample in our main analysis, but we will include it in robustness checks.

of the WoOn-Survey, who were surveyed from August 2017 - March 2018. We focus on the respondents for whom all variables of interest are available, which gives us a sample of 56,283 respondents. Summary statistics for the 2018 sample can be found in Table 5.4.1. The cross-sectional dataset consists of households living in owner-occupied housing (66.2 percent), as well as in rental housing, where we distinguish between the free rental sector (9.1 percent) and social housing (24.7 percent).[15]

Our main variables of interest are whether a household has done energy-efficiency home improvements and the energy efficiency of their home. We define our *home improvements*-variable as a binary variable that is equal to 1 if a household has undertaken at least one of these measures and zero otherwise. The 2018 survey contains more information on the exact type of home improvement done, providing a set of binary variables indicating whether a household has obtained (i) double glazing, (ii) roof, wall or floor insulation, (iii) the installation of solar panels, (iv) or the installation of a boiler panels (v) or other energy saving facilities in the past 5 years. Our *energy efficiency*-variable is a binary variable based on the energy label of the house, which is provided by the Dutch government (RVO). The variable is equal to 1 if a household lives in a house with an A or B energy label, and zero otherwise. Energy labels range from A to G, with A being the most energy efficient and G the least efficient. We define houses with an energy label of A or B as energy efficient and houses with another label as energy inefficient.

Table 5.4.2 provides summary statistics for energy efficiency and home improvement. Only 24.3 percent of households in our sample live in energy-efficient homes. The fraction of households in the 2018 sample that did improve home energy efficiency is 56.8 percent. This is relatively high, and can in part be explained by the fact that we look at home improvements conducted over a time period of 5 years. Most households improve their home by taking a more efficient boiler (34.6 percent) or installing double

[15] There are long waiting lists to get social housing. In at least a quarter of all municipalities, households have to wait more than 7 years.

Variable	Mean	SD	Min	Max
Household Characteristics				
Spendable household inc.(euro)	43,490	31,203	11	1,274,501
Total wealth	264,771	299,400	0	2,498,334
Net wealth	152,846	250,575	-199,918	1,994,929
Age 17-24	0.023	0.149		
Age 25-34	0.133	0.340		
Age 35-44	0.146	0.353		
Age 45-54	0.193	0.395		
Age 55-64	0.202	0.401		
Age 65-74	0.180	0.384		
Age 75+	0.123	0.328		
Young child	0.086	0.281		
Partner	0.613	0.487		
Higher education	0.338	0.473		
House Characteristics				
House size (sq. mtr)	123.925	68.824	14.000	1,000.000
Construction $<$ 1945	0.171	0.376		
Construction 1945-1959	0.090	0.286		
Construction 1960-1969	0.135	0.341		
Construction 1970 - 1979	0.179	0.383		
Construction 1980 - 1989	0.154	0.361		
Construction 1990 - 1999	0.123	0.329		
Construction 2000 - 2009	0.096	0.295		
Construction $>$ 2010	0.052	0.223		
Single-standing	0.160	0.367		
Two under one roof	0.144	0.351		
Corner	0.130	0.336		
Row and other	0.295	0.456		
Flat	0.272	0.445		
Sector				
Social	0.247	0.431		
Rent	0.091	0.288		
Occupied	0.662	0.473		
Energy expenditures				
Annual gas expenditures (euro)	1,156	513	227	6,276
as part of income	0.036	0.047	0.001	1.935
Annual electricity expenditures (euro)	924	345	291	2,660
as part of income	0.028	0.039	0.001	1.955
Annual water expenditures (euro)	188	56	96	597
as part of income	0.006	0.008	0.000	0.486
Utility expenditures (euro)	2,268	748	624	8,822
as part of income	0.068	0.065	0.002	1.961
Heating type	1.777	1.789	1.000	8.000
Number of persons in hh	2.230	1.173	1.000	5.000

Note: Based on 56,283 observations from the WoON-survey (2018). For for net wealth, we have 55,418 observations. We restrict all energy expenditures as a share of income to be at most equal to two. We have 8 dummies for the different heating types (central heating boiler, wood-burning heating device, pellet stove, gas heater, heat pump, block/district heating, city heating, other). In our sample, 88% of respondents have a central heating boiler. The variable 'heating type' displays the average heating type.

Table 5.4.1: Household, house characteristics, and energy expenditures (2018).

Variable	Energy Eff.	A-Label	B-Label	C-Label	D-Label	E-Label	F-Label	G-Label
Mean (Overall)	0.243	0.089	0.155	0.310	0.076	0.130	0.113	0.128
Social	0.198	0.090	0.108	0.365	0.048	0.265	0.077	0.047
Rent	0.198	0.085	0.114	0.226	0.030	0.192	0.070	0.283
Owner-occupied	0.266	0.089	0.177	0.300	0.092	0.071	0.132	0.140
Variable	Home Improv.	Glass	Insulation	Solar	Boiler	Other		
Mean (Overall)	0.568	0.263	0.196	0.085	0.346	0.089		
Social	0.497	0.248	0.144	0.054	0.308	0.048		
Rent	0.383	0.186	0.091	0.024	0.228	0.043		
Owner-occupied	0.620	0.279	0.232	0.105	0.376	0.111		

Note: Based on 56,283 observations from WoON-survey (2018). *Home improvements*-variable is a binary variable equal to 1 if a household has undertaken at least one type of home improvement measure in the last 5 years (double glazing, roof, wall or floor insulation, the installation of solar panels, or the installation of boiler panels, or other energy-saving facilities), and zero otherwise. *Energy efficiency*-variable is a binary variable based on the energy label of the house and equal to 1 if a household lives in a house with an A or B energy label, and zero otherwise. Energy labels range from *A* to *G*, with *A* being the most energy-efficient, *G* the least efficient.

Table 5.4.2: Energy efficiency and home improvements (2018)

glass (26.3 percent).[16]

Our main other variables of interest are households' disposable income and wealth. Household disposable income is measured as gross income including social benefits and net of paid income transfers, insurance premiums, and taxes on income and capital. The average income is equal to 43,490 euro. We consider total wealth according to the official definition of Statistics Netherlands (i.e., the total value of assets, which includes savings, stocks and bonds, enterprise equity, and housing) as well as net wealth (wealth minus debt, including mortgage debt).[17] Information about both wealth variables comes from tax registry data (Statistics Netherlands) as well. The average total wealth in the resulting sample is 264,771 euro (with a median of 217,972), and the average net wealth is equal to 152,846 euro (with a median of 56,652).[18] [19] In the remainder of this paper, we are particularly interested in how home improvement and/or buying an energy-efficient house affect the accumulation and distribution of wealth.

Finally, to assess whether energy efficiency-enhancing home improvements reduce energy expenditures, we also utilize information from the utility operator (Statistics Netherlands) on households' annual gas and electricity expenditures, as well as households' annual utility expenditures, which are measured as their annual energy expenditures plus water bills. Households spend about 6.8 percent of their income on utilities. Most of energy expenditures (about 3.6 percent) are spend on natural gas.

[16] We also examined the geographical distribution of home improvements. In the urban core of the Netherlands ("Randstad"), 54.1 percent of households did a home improvement. This is less than in the periphery, where 58.3 percent of households did a home improvement. Regarding energy efficiency, 23.8 percent of households have an energy-efficient home in the Randstad. This is again less than in the periphery, where 24.6 percent of households have an energy-efficient home. For the potential urban economic implications of energy efficiency see Glaeser and Gyourko (2005) and Kahn and Kok (2014).

[17] Housing wealth is based on the (one year lagged) assessed value of the house which is updated using price indices. Secondary homes, vacation homes, and investment properties are also included. Durable goods and cash holdings are not included due to a lack of data. Pension and life annuities are also not included.

[18] We exclude households whose income is negative and households with an income greater than 2,500,000 euro. We also exclude households with negative total wealth and households with a total wealth value greater than 2,000,000 euro. Finally, we exclude households with net wealth lower than -200,000 euro and households with net wealth higher than 2,000,000 euro.

[19] Controlling for the composition of the Dutch society using household weights reduces average (net) wealth. Specifically, once we incorporate household weights, the weighted average of total wealth is 241,678 euro (with a median of 191,668) and the weighted average of net wealth is given by 134,977 euro (with a median of 35,576).

5.5 Energy efficiency, home improvement, and the effect of income

We start our analysis by examining the relationship between income and home improvements (intensive margin) as well as sorting into energy-efficient homes (extensive margin). We also explore the heterogeneity in the types of home improvements, the reasons for undertaking home improvements, and the role of subsidies.

5.5.1 Home improvements

We model the probability that the household has improved the energy efficiency of the home in the last 12 months:

$$\text{Home improvement}_i = \beta \log \text{Inc}_i + \theta X_i + \delta h_i + \alpha_j + \eta_i, \tag{5.5.5}$$

where $\log \text{Inc}_i$ is the natural logarithm of the income of household i. We include a set of household characteristics, X_i, and home characteristics, h_i, as control variables. The household characteristics that we consider are age, gender, and education.[20] The home characteristics we consider are the type of house, house size, the type of heating system, and the year of construction.[21] α_j are location fixed effects, and η_i is the error term. We estimate (5.5.5) using OLS and cluster standard errors at the COROP level.[22]

Table 5.5.3, columns 1-5, reports the results on the probability that a household has improved the energy efficiency of their house over the past five years, as specified in

[20] To control for education, we include a dummy indicating whether the respondent has a university degree or finished higher professional education. To proxy for household structure, we obtain information on the number of persons in the household (which is particularly useful for modeling energy expenditures) and include a dummy variable indicating whether the respondent has children under the age of 2.

[21] We types of homes we distinguish between are single-standing home, two under one roof, corner house, in between two other homes, flat/apartment, and other homes. The heating types we distinguish between are boiler, block, district or city heating, heating by heaters, other heating types. The house size is measured in square meters.

[22] We estimate the relationship using COROP region (work-living areas, NUTS2 classification). We verify that our results hold using more granular location fixed effects in an earlier survey wave, at the ZIP-code and municipality level (NUTS3 classification).

Table 5.5.3: Home Improvements and Energy Efficiency - Baseline Estimates (2018)

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	Home Improvement			Energy Efficiency				
	Baseline	Sector	Owner-Occupied	Baseline	Sector	Social rent	Free rent	Owner-Occupied
Income (log)	0.0698***	0.0523***	0.0598***	0.0581***	0.0531***	0.0348***	0.0281***	0.0601***
	(0.005)	(0.005)	(0.006)	(0.008)	(0.007)	(0.009)	(0.009)	(0.007)
Social		-0.0560***			-0.0097			
		(0.008)			(0.013)			
Rent		-0.1385***			-0.0583***			
		(0.008)			(0.007)			
Household Characteristics	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
House Characteristics	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Location FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Observations	56,283	56,283	37,267	54,170	54,170	13,572	4,832	35,766
Adjusted R-squared	0.091	0.096	0.083	0.064	0.066	0.056	0.033	0.076

Note: Estimation results for Eq. (5.5.5) (columns 1–3) and Eq. (5.5.6) (columns 4–8), based on the WoON-survey (2018). We estimate both equations with OLS, and include location fixed effects. Standard errors are clustered at the COROP-level, *** p<0.01, ** p<0.05, * p<0.1.

Eq. (5.5.5). The results in column 1 suggest that the effect of income is positive and statistically significant at the one percent significance level. The effect is also economically sizeable against the average home improvement rate of 0.57. In particular, a one percent increase in income raises the probability of undertaking energy efficiency-enhancing home improvements by 7 percent. The effect decreases somewhat once we control for the type of ownership, in column (2), since income and the type of ownership (i.e., the tenure choice) are strongly correlated. Both social and free rental sector houses are less likely to experience home improvements. This is because these households must rely on the owner of the house to make home improvements. Therefore, a change in households income is not directly associated with the probability that energy efficiency enhancements are undertaken in their home.[23] We re-estimate Eq. (5.5.5) for the sub-sample of owners. The results, which are reported in columns 3 confirm that the effect of income on home improvements is entirely driven by the owner-occupied market segment. This implies that regulations (e.g., subsidies) to make it more financially attractive for a household to improve the energy efficiency of their house are mainly effective for the owner-occupied housing sector.

To explore heterogeneity across types of home improvements, we estimate the propensity to carry out different types of home improvements. In particular, we estimate the relationship separately for home improvements in the form of (i) double glazing, (ii) roof, wall or floor insulation, (iii) the installation of solar panels, (iv) or the installation of a boiler (v) or other energy saving facilities. The results are reported in Table 5.12.9 in Appendix A3. A one percent increase in income leads to the largest increase in the probability of installing a boiler and of insulating the home. The effect is smallest for the propensity to install solar panels. This suggests that, as income rises, households tend to prioritize home improvements that yield the largest energy efficiency gains.

[23] while the energy savings are for the households themselves – as they typically pay the energy bill –, these households do not benefit from the effect of energy efficiency enhancements on house values. This split incentive problem is well established and reduces the likelihood of implementing energy efficiency measures (e.g., see Bird and Hernández, 2012).

5.5.2 Energy efficiency

We next model the probability that a household lives in an energy efficient house:

$$\text{Energy efficiency}_i = \beta \log \text{Inc}_i + \theta X_i + \delta h_i + \alpha_j + \varepsilon_i, \tag{5.5.6}$$

where ε_i is the error term and all other variables are defined as before.[24] We estimate (5.5.6) using OLS and cluster standard errors at the COROP level.

Table 5.5.3, columns 4-8, reports the estimates using the indicator of whether the home is energy efficient as dependent variable, see Eq. (5.5.6). The results in column 4 suggest that the effect of income is positive and statistically significant at the one percent significance level. A one percent increase in income raises the probability of residing in an energy-efficient home by 5.8 percent. This effect remains stable when controlling for housing tenure in column (5).

To explore heterogeneity across tenure types, we re-estimate Eq. (5.5.6) for the subsample of each housing sector. Columns (6)–(8) confirm that income is positively associated with the probability of residing in an energy-efficient home across all tenure types. However, the relationship is somewhat weaker in the rental sector, especially for households in the free rental sector.

As temporary energy labels do not take into account any measures to improve energy efficiency in the home, homeowners can request a final energy label. We re-estimate the probability of residing in a more energy-efficient home for an increase in income using data on final energy labels, which are available for roughly half of the respondents within our sample.[25] The results are reported in column 2 of Table 5.12.10 in Appendix A3, show comparable results to those using temporary labels. We also re-

[24] We use temporary energy labels as a dependent variable, as we have data available on temporary labels for all respondents in our sample, since all homes in the Netherlands were assigned a temporary energy label in 2015. Because part of the temporary labels were assigned according to the year of house construction, there is a strong negative correlation (-0.9) between the year of construction and the energy label. We account for this by excluding the construction year from our control variables in the estimation.

[25] We also estimated a multinomial logit model using the different energy labels. The results are in line with our main findings. A unit increase in log income (100%) increases the relative risk ratio for energy label A or B versus G by a factor of 1.5 while increasing the ratio by 1.07 for energy label F. Therefore, as income increases, households are more likely to eventually have an A or B energy label.

estimate Eq. (5.5.6) using the energy index. This is a numerical measure of the energy performance of a home, which is inversely related to energy performance, meaning that a *lower* energy index reflects a higher energy performance.[26] Accordingly, the effect of income on the energy index is negative and statistically significant at the one percent level. This further confirms the positive relationship between income and the probability of residing in an energy efficienyt home.

5.5.3 Reasons for energy efficiency enhancements

Why do households undertake energy efficiency enhancing home improvements? This question is particularly relevant for understanding the underlying motivations behind energy efficiency investments, especially given prior evidence suggesting that their returns may be negative (e.g., Fowlie et al., 2018). The survey asked households who undertook energy efficiency-enhancing improvements to indicate their main reasons. The results are reported in Appendix A4. Table 5.13.11 Among the 23,485 respondents, approximately half reported that these improvements were necessary due to maintenance. About 25 percent believed the investment would pay off financially, while 20 percent did home improvements to make their home more comfortable. Only 1 percent cited increased marketability of the home as their main motivation.

The survey also asked households who did not undertake energy efficiency enhancing home improvements to explain their reasons for abstaining. Among the 11,310 respondents, the most common answer was that their home was already energy efficient (38 percent). Financial constraints were also mentioned often: 17 percent reported that home improvements were outside their budget, and 12 percent said they lacked sufficient savings. Additionally, 7 percent of households stated they did not want to

[26] An energy label of $A++$ corresponds to an energy index below 0.6, while an energy label of G corresponds to an energy index greater than 2.7.

renovate, and 5 percent indicated a lack of knowledge about available options.[27]

The survey also asked households under which conditions they would consider undertaking (additional) home improvements in the future. Among all households indicating that they would be willing to undertake energy efficiency enhancements in the future, 21 percent of respondents indicated they would be willing to do so even if the net present value is negative. This suggests that a non-negligible share of households is be motivated by non-financial factors when making home improvement decisions. Figure 5.13.3 in Appendix A4 shows that these households tend to have higher incomes, pointing to a correlation between income and green preferences. This pattern is not consistent with a purely financial literacy explanation, where higher-income households better recognize and capitalize on returns, but rather indicates that green preferences likely play an important role.

A similar pattern is observed in housing choices. The survey also asks whether households would be willing to pay a premium for renting an energy-efficient home. Only 8.9 percent of those willing to pay such a premium stated they would do so even if the additional cost is not fully offset by lower energy bills. This shows that the perceived ability to earn back the investment plays an important role in renters' decisions to pay for energy efficient housing. Given that renters tend to have lower incomes, the lower willingness to pay a premium without a clear financial return further suggests a positive correlation between green preferences and income.

5.5.4 The role of subsidies

Subsidies can play an important role in encouraging households to undertake home improvements. As outlined in the institutional context, the Netherlands has introduced

[27] We examine how these motivations vary with households' income. Table 5.13.12 in Appendix A4 shows that an increase in income makes it more likely that households undertake home improvements in order to make their home more pleasant or because of environmental considerations, while an increase in income makes it less likely that home improvements are necessary due to maintenance. Table 5.13.13 shows how the probability of each reason not to make home improvements also changes in income. An increase in income raises the likelihood that the home is already efficient, as well as the probability that respondents did not get to making home improvements yet and plan to move. An increase in income reduces the likelihood that households have an investment that is out of budget.

a large subsidy program aimed at supporting energy efficiency measures, which may help overcome financial barriers. About 14.2 percent of the sample reports having received a subsidy. The uptake varies both by type of home improvement undertaken, and by households' income. For instance, approximately 50 percent of households that installed solar panels indicates that they have received a subsidy, compared to just 11 percent of those who installed a boiler. Importantly, subsidy uptake increases monotonically with income across the different home improvement types, as shown in Table 5.14.14 in Appendix A5.

Given that our measure of income does not account for subsidies, we re-estimate the results of Eq. (5.5.5) and add a subsidy-dummy additional control variable. The results are reported in Table 5.14.15 in Appendix A5. Once we control for subsidies, the marginal effect of income becomes substantially larger: a one percent increase in income is associated with a 14.2 percent higher probability of undertaking home improvements – which is twice as large as our baseline estimate.[28]

5.5.5 Wealth or income?

We assess whether income or wealth is more strongly associated with undertaking energy-efficiency improvements or sorting into more energy-efficient homes, by including total asset values alongside income in the estimation of Eq. (5.5.5) and (5.5.6). The results are reported in Table 5.14.16 in Appendix A5. The results, reported in columns 1-2 of Table 5.14.16 in Appendix A5, show that both income and wealth are positively and significantly associated with these outcomes. The magnitude of the effect is notably larger for income than for wealth, suggesting that liquid financial resources are more important in determining households' decisions to invest in energy efficiency than their accumulated assets.

Although total asset value serves as a proxy for wealth, it does not account for

[28] While we also find a positive association between receiving a subsidy and the likelihood of undertaking home improvements, this coefficient should be interpreted with caution as there potentially is reverse causality. Specifically, households may receive subsidies because they undertake improvements, or undertake them because they can get a subsidy for it. The main takeaway from this analysis is that the effect of income remains robust when controlling for subsidy receipt.

households' liabilities and therefore may overlook the role of debt in financing energy efficiency investments. In practice, households can and do attract debt to fund such improvements. Many Dutch households, particularly low-income ones, indicate that it is difficult to find adequate financing to undertake home improvements (Havlinova, Heerma van Voss, Zhang, Van der Molen, and Caloia, 2022).[29] To examine the role of debt, we re-estimate Eq.(5.5.5) and Eq.(5.5.6) using net wealth rather than total wealth. The results are reported in columns 3–4 of Table 5.14.16 in Appendix A5. The effect of net wealth on the propensity to undertake energy-efficiency home improvements is similar to that of total wealth, suggesting that debt play a limited role in financing these types of enhancements. In contrast, the effect of net wealth on the probability of residing in a more energy-efficient home is considerably stronger than that of total wealth. This rather implies that equity may be an important channel through which households finance the purchase of more energy-efficient housing.

5.5.6 The effect of the COVID-19 pandemic

Our analysis has primarily focused on the 2018 survey wave. Although a later wave from 2021 is available, the 2021 survey was conducted during the COVID-19 pandemic. Due to lockdowns, the sampling period was split into two parts and the response rate was lower. Moreover, households faced other challenges during this period, making home improvements or purchasing energy-efficient housing less of a priority. Despite these challenges, we examine the 2021 WoON data to verify whether our main findings hold. The descriptive statistics and regression results for home improvement and energy efficiency are in Appendix A6.

We observe that households were slightly less likely to undertake home improvements in 2021, with 53 percent doing so compared to 57 percent in 2018. Meanwhile, the share of energy-efficient housing rose sharply from 24 to 45 percent. This is in part due to the fact that the 2018 statistics are based on preliminary energy labels, while

[29] In our sample, approximately 8 percent of households indicated they borrowed to finance home improvements, and among them, 64 percent used mortgage financing.

the 2021 statistics are based on the final labels.[30] Apart from this, the Dutch Climate Agreement between companies and (government) organizations that came into effect in 2019 has also stimulated substantial investments in energy efficiency. Although energy prices increased, households spend slightly less of their income on utilities (6.2 percent in 2021, compared to 6.8 percent in 2018). Importantly, while the regression results show that the marginal effect of income is somewhat lower in 2021 than in 2018, our main findings remain robust.

5.6 Energy expenditures and energy savings

To explore how energy efficiency affects the wealth distribution on the one hand and CO2 emission reductions on the other, we examine how energy efficiency enhancing home improvements and sorting into energy-efficient housing affects energy consumption both in euro and in physical quantities (e.g., KWh, m^3). In particular, we estimate households' energy consumption as a fraction of income:

$$\begin{aligned}\text{Energy consumption}_i(\%) = \gamma_1 \text{Home improvement}_i + \gamma_2 \text{Energy efficiency}_i + \\ \phi_1 \text{Number of persons}_i + \phi_2 \text{Heating type}_i + \theta X_i + \delta h_i + \alpha_j + \omega_i,\end{aligned} \tag{5.6.7}$$

where number of persons$_i$ captures the number of persons in the household and heating type$_i$ are dummy variables for the type of heating system being utilized. Again, X_i are housing characteristics, h_i household characteristics, α_j location fixed effects, and ω_i is the error term. As a dependent variable, we use the total utility costs, and also provide estimates for gas, electricity, and water separately.[31]

[30] In the 2018 statistics, final energy labels are only available for roughly half of the sample.

[31] A potential reason for caution in the estimation of Eq. (5.6.7) is that it could be affected by a rebound effect. That is, as soon as a household does home improvement or owns an energy-efficient home, this can lead to a higher energy consumption. While there is mixed evidence on the rebound effect, as some find such an effect (Aydin et al., 2017) while others do not (Kattenberg et al., 2023; Fowlie et al., 2018), the potential presence of a rebound effect would imply that we underestimate the true effect of energy efficiency on energy consumption. However, we would effectively capture the actual energy expenditure (including any behavioral considerations) and its implications for wealth accumulation and CO2 reduction benefits.

Table 5.6.4: The Effect on Energy Consumption (2018)

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
	Gas/Income		Electricity/Income		Water/Income		Utility/Income
	in euro	usage (in m^3)	in euro	usage (in KWh)	in euro	usage (in m^3)	in euro
Home Improvements	-0.0023***	-0.0028***	-0.0021***	-0.0070***	-0.0003***	-0.0002***	-0.0047***
	(0.0005)	(0.0006)	(0.0004)	(0.0012)	(0.0001)	(0.0001)	(0.0005)
Energy Efficiency	-0.0076***	-0.0113***	-0.0010**	-0.0031***	-0.0003*	-0.0002***	-0.0088***
	(0.0006)	(0.0007)	(0.0005)	(0.0017)	(0.0001)	(0.0001)	(0.0008)
Household Characteristics	Yes	Yes	Yes	Yes	Yes	Yes	Yes
House Characteristics	Yes	Yes	Yes	Yes	Yes	Yes	Yes
ZIP-code FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Observations	53,805	53,805	53,809	53,809	53,821	53,821	53,782
Adjusted R-squared	0.082	0.079	0.048	0.028	0.028	0.018	0.108

Note: Estimation results for Eq. (5.6.7) for various types of energy expenditures, based on the WoON-survey (2018). We estimate the equation with OLS, and include location fixed effects. Standard errors are clustered at the COROP-level, *** p<0.01, ** p<0.05, * p<0.1.

The estimation results of Eq. (5.6.7) are reported in Table 5.6.4. The reduction in utility costs due to home improvements is largely driven by a decrease in the gas expenditures, which explains 48.9 percent of the overall reduction in utility costs. In case of sorting into energy-efficient homes, this effect becomes even stronger, with the reduction in gas expenditures explains 86.6 percent of the overall reduction in utility costs. We find evidence that home improvements reduce utility expenditures as a share of income by -0.5 percentage points. This is a reduction of the average annual utility expenditures as a percentage of income by approximately 6.4 percent.[32] The utility expenditures as a share of income of respondents living in an energy efficient house are on average -0.9 percentage points lower, bringing forward a reduction in the average annual utility expenditure as a percentage of income by 11.5 percent. Interestingly, the marginal effect of sorting into a more energy-efficient home is larger when measured in actual energy usage than in euro spent on gas and electricity. This suggests that households in energy-efficient homes may be paying a lower price per unit of energy.[33]

We run several robustness checks on the utility expenditure regression. These are reported in Table 5.16.21 in Appendix A7. First, we re-estimated the utility expenditure regression using data from 2021. We find that the marginal effect of home improvements is about 2.5 times lower than our baseline estimate. The coefficient on living in an energy-efficient home is slightly lower than our baseline estimate, but still falls within the 95 percent confidence interval. An explanation for the reduced impact of home improvement could be that the type of home improvement undertaken changed between 2018 and 2021. Specifically, the percentage of households that improved their homes by installing double glass, a new boiler, heat pump, or insulation decreased.

[32] The average annual utility expenditures as a percentage of income are equal to 7.8 percent, see Table 5.4.1).

[33] We evaluate the heterogeneity of the effects of various types of home improvement on utility expenditures. The results, which are reported in Appendix A7, Table 5.16.20, indicate that solar panel installation leads to the largest reduction in utility expenditures as a share of income, while double glazing does not appear to lead to a statistically significant reduction in utility expenditures. We also explore the heterogeneity in the effect of distinct energy labels on utility expenditures. The results reveal that utility expenditures are significantly lower for houses with an A-, B-, or C-energy label. Households living in a house with an D-, E- of F-label also have significantly lower utility expenditures compared to households who live in a house with a G-label.

Importantly, these types of home improvement are typically the first to be undertaken and have a strong effect on energy savings. Instead, the number of households that installed solar panels increased from 8.5 to 15.3 percent in the 2021 data (see Table 5.4.2 and Table 5.15.18). Second, we re-estimated the effect for the 95th percentile of energy expenditure to income in 2018 (quantile regression). This corresponds to the average energy expenditure to income of households in the lowest income quartile. The effect of home improvement and energy efficiency become about twice as large, as the first home improvement that a household undertakes is typically the most beneficial in terms of the energy savings generated. Third, we assess whether the effects of home improvements on energy consumption are lower when the home is more energy efficient. The interaction effect between home improvements and energy efficiency is not statistically significant, however. Finally, Adelino and Robinson (2023) argue that energy efficiency enhancing home improvements typically coincide with other renovations in the home, effectively reducing energy savings. In our data, inside and outside changes are negatively correlated with home improvements, indicating that households do not tend to carry these out simultaneously. While other renovations, like adding a sun room, or a dormer, a new kitchen, or changing the house plan increase energy expenditures, our main results remain quantitatively similar.

Based on our baseline estimates, reported in Table 5.6.4, the average annual reduction in utility expenditures resulting from home improvements and living an energy-efficient home amounts to 587 euro, which constitutes 25.9 percent of the average total utility expenditures. We determine the present value of these average savings, based on an investment horizon of 15 years and a real interest rate rate of 5 percent, the present value of savings yields 6,093 euro.[34] These gross savings are substantial, as they amount to 3.2 percent of median wealth, 17.1 percent of median net wealth, or 2.1 percent of the average house price in the Netherlands in 2018. According to our regression estimates, sorting explains about 65 percent of these savings.

[34] We provide calculations for alternative investment horizons and real interest rates in Table 5.16.22 in Appendix A7. For comparison, Fowlie et al. (2018) report an average life-span of home improvements of 16 years and use a 3 - 7 percent discount rate.

Although the costs for undertaking energy efficiency home improvements can vary substantially across suppliers, time, and type of home improvement[35], the our baseline energy savings suggest that the annualized returns are likely to be low or even negative. While our energy savings are most likely an underestimate (due to a potential rebound effect), it does suggest that energy efficiency investments investments might not always be worthwhile - which is in line with Fowlie et al. (2018).[36]

5.7 Wealth inequality, CO emissions, and public policy scenarios

We consider the effects of energy savings on the distribution of wealth and CO2 emission reductions. Panel A of Table 5.6.4 reports the current footprint per quartile of income.[37]. Households in the first quartile spend much a much larger share of their income on utilities (11.4 percent) than households in the upper quartile (3.8 percent). In terms of actual energy usage, households in the upper quartile use 1.5 times more gas, almost 2 times more electricity, and more than 2 times more water, than households in the lower quartile.

We estimate the CO2 emissions associated with household energy consumption[38] and assign a monetary value to these emissions using the social cost of carbon. While

[35] For example, the costs associated with the installation of double glass range from 2,000-3,000 euro for a standard row house, and the costs of solar panels are between 3,000-4,000 euro. Buying an A-energy label house instead of an D-label house costs about 5,000 euro more (Aydin and Brounen, 2016).

[36] The investment horizon of certain home improvement may be longer, so it might well be a more favorable investment opportunity in some cases (see for example the returns to insulation as estimated by Kattenberg et al., 2023).

[37] The threshold are as follows: 1^{st} Quartile $<$ 25k euro, 2^{nd} Quartile 25k-38k euro, 3^{rd} Quartile 38k-55k euro, 4^{th} Quartile $>$55k euro

[38] We use a m^3 gas to MMBTU conversion factor of 0,0366, a KWh electricity to MMBTU conversion factor of 0,003404, a MMBTU to CO2 conversion factor of 53,07kg, and 0.4kg CO2 per cubic meter of water. For the gas and electricity conversion factors, we use a Dutch source (www.energieconsultant.nl) but the numbers are similar if we look at the U.S. Energy Information Administration (EIA). The MMBTU to CO2 conversion factor comes from the EIA. The CO2 per cubic meter is 0.34 - 0.46 kg according to www.brightest.io.

estimates of the social cost of carbon vary substantially in the literature,[39] we adopt a conservative estimate of 200 euro per ton. Based on this benchmark, we find that households in the top income quartile generate approximately 7,500 euro worth of CO2 emissions over a 15-year horizon, which is about 1.5 times the emissions cost of households in the bottom income quartile.

We use a similar approach to examine the energy savings and CO2 emission reductions resulting from the home improvement and sorting patterns we observe in our data using the estimates in Table 5.6.4. The results are reported in Panel B. show that while low-income households are less likely to undertake home improvements, and tend to realize lower nominal present value energy savings when they do, the energy savings are substantial relative to their wealth. For the lowest quartile of income, the energy savings represent 35.5 percent of net wealth while this is only 7.3 percent for the upper quartile. Instead, we find the opposite for CO2 emission reduction. Households in the upper income quartile save about four times as much on energy (4,000 euro compared to 1,000 euro) due to the larger footprint of their homes. Their total energy savings amount to 2.7 billion euro, accounting for 49.5 percent of the aggregate savings over a 15-year period. Moreover, the unrealized CO2 emission reductions in their remaining non-efficient homes represent 38.0 percent (equivalent to 3.9 billion euro) of the total remaining mitigation potential. Approximately 90 percent of these benefits are concentrated in the owner-occupied housing sector. The difference between the distribution of energy savings relative to wealth and the distribution of CO2 emission savings – illustrated in Figure 5.7.2 and in Panel B of Figure 5.2.1 – highlights the underlying policy trade-off.[40]

[39] Fowlie et al. (2018) report abatement costs of 201 to 285 dollar per ton of CO2 for home improvements. Rennert, Errickson, and Prest (2022) estimate a social cost of carbon of 185 dollar per ton, while Kikstra, Waidelich, Rising, Yumashev, Hope, and Brierley (2021) report a range of 185–200 dollar per ton based on climate scenarios aligned with the Paris Agreement (SSP1-1.9 and SSP1-2.6), which incorporate climate feedback and economic dynamics. More recent work by Bilal and Känzig (2024) suggests this cost may be as high as 1,367 dollar per ton.

[40] This trade-off is also present in the 2021 data, see Figure 5.16.4. The difference in energy savings has become stronger as poorer households were more negatively affected in terms of wealth during the Corona pandemic. Wealthy household have reduced their CO2 emissions most, but still remain more brown than poorer households.

Table 5.7.5: Distribution of Wealth, Energy Savings, and CO2 benefits (2018)

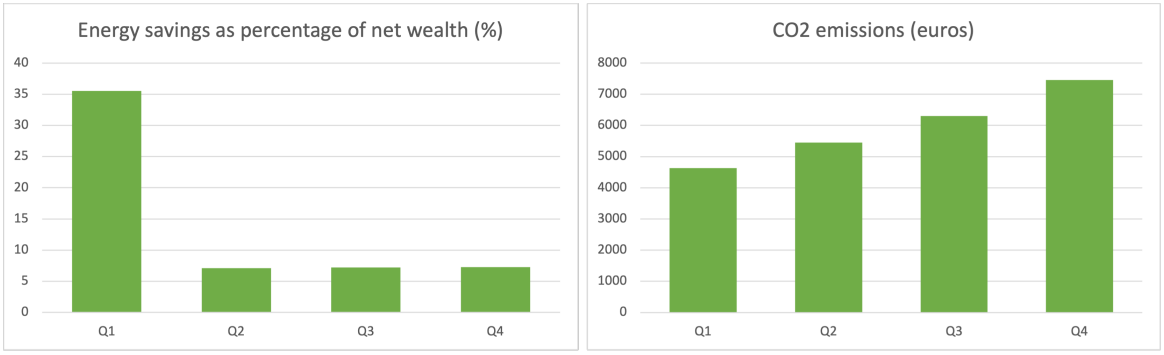
	1^{st} Quartile	2^{nd} Quartile	3^{rd} Quartile	4^{th} Quartile
Panel A: Current footprint per quartile of income				
Mean Income (euro)	18,810	31,359	45,856	78,184
Utility costs (as % of income)	11.4	6.8	5.3	3.8
Gas costs (as % of utility costs)	52.4	51.5	50.4	50.5
Electricity costs (as % of utility costs)	39.5	40.2	41.1	41.2
Water costs (as % of utility costs)	8.1	8.3	8.4	8.3
CO2 emissions (euro, 15 years)	4,629	5,449	6,300	7,453
Gas (m^3/year)	1,131	1,313	1,487	1,754
Electricity (kWh/year)	2,118	2,683	3,314	3,984
Water (m^3/year)	71	96	120	143
Panel B: Savings per quartile of income				
PV of energy savings (euro, 15 years)	2,637	4,396	6,428	10,960
as % of median wealth	26.9	2.4	2.6	3.0
as % of median net wealth	35.5	7.1	7.2	7.3
PV of CO2 savings (euro, 15 years)	972	1,612	2,358	4,020
Total PV CO2 (mil. euro, 15 years)	582	839	1,297	2,705
as % of overall PV	10.7	15.4	23.7	49.5
Remaining CO2 savings (mil. euro, 15 years)	1,764	2,060	2,614	3,944
as % of overall remaining PV	17.0	19.8	25.2	38.0
in owner-occupied housing (%)	17.2	58.0	80.0	90.5
in social housing (%)	57.8	27.3	11.5	3.9
Panel C: Policy scenarios				

Policy 1: Provide energy efficient housing and a home improvement for households in the first income quartile.
Policy 2: Provide energy efficient housing and a home improvement for households with a below median income.
Policy 3: Provide energy efficient housing and a home improvement for all households.

	Post (15 years)	Policy 1	Policy 2	Policy 3
Inequality & Poverty				
Wealth Gini (current: 57.6)	57.3 (-0.5%)	57.4 (-0.3%)	57.2 (-0.7%)	56.7 (-1.6%)
Net Wealth Gini (current: 77.0)	76.1 (-1.2%)	76.6 (-0.5%)	76.2 (-1.0%)	74.4 (-3.4%)
Wealth Atkinson($e = 0.5$, current: 33.7)	33.3 (-1.2%)	33.2 (-1.5%)	32.8 (-2.7%)	31.9 (-5.3%)
Net Wealth Atkinson($e = 0.5$, current: 38.7)	38.5 (-0.5%)	38.6 (-0.3%)	38.5 (-0.5%)	37.8 (-2.3%)
Wealth Atkinson($e = 1.0$, current: 74.8)	71.7 (-4.1%)	70.5 (-5.7%)	68.6 (-8.3%)	65.5 (-12.4%)
Net Wealth Atkinson($e = 1.0$, current: 74.2)	72.6 (-2.9%)	71.7 (-3.4%)	70.9 (-4.4%)	69.0 (-7.0%)
Climate				
CO2 savings (mil. euro, 15 years)	8,962	+1,764	+3,824	+10,382
as % of all potential savings (Policy 3)	-	17.0	36.8	100.0
Costs				
100% funding (costs in bil. euro)		14.1	24.2	41.7
Low costs (3,000 euro per house)		7.1	12.1	20.9
High costs (9,000 euro per house)		21.2	36.4	62.6

Note: Based on the WoON-survey (2018). In panel A, we used a m^3 gas to MMBTU conversion factor of 0.0366, a KWh electricity to MMBTU conversion factor of 0.003404, and a MMBTU to CO2 conversion factor of 53.07kg. We assume 0.4kg CO2 per cubic meter of water and a social cost per ton of CO2 of 200 dollars (185 euro). In panels B and C, we use a 15-year investment horizon and a 5% discount rate. In panel B, the total and remaining savings, and in panel C, the inequality indices, CO2 savings, and funding costs are calculated using sampling weights. The calculations in panels B and C are based on the estimates shown in Table 5.6.4. The costs in panel C are based on 6,000 euro per household, where 9,000 is used as an upper bound and 3,000 euro as a lower bound.

Figure 5.7.2: The energy-efficiency paradox (2018)



Note: The left panel displays energy savings in euro as a percentage of net wealth, by income quartile. The right panel displays the current carbon footprint of households by income quartile, as measured by the CO2 emissions associated with their energy consumption. For more details, see Table 5.7.5.

Panel C explores this policy trade-off. We first report the current level of (net) wealth inequality (based on the Gini coefficient) and a welfare equivalent that weights in poverty more heavily (based on the Atkinson index).[41] The post-column indicates the level of inequality based on the current distribution of home improvements and sorting patterns into energy-efficient homes. Surprisingly, both the net and total wealth Gini-coefficients are expected to decline over the 15-year horizon based on the investments made in 2018. For example, the net wealth Gini-coefficient decreases by 1.2 percent when accounting for the cumulative energy savings over this period.[42] Even though households in the higher quartiles are more likely to make home improvements, this effect is outweighed by the relatively larger gains, in proportional terms, that lower-income households achieve from having an energy-efficient house. This effect becomes even more pronounced when considering the Atkinson indices.

We use our estimation results to evaluate the impact of several policy scenarios. In Policy 1, households in the lowest income quartile who either do not live in an energy-

[41] To be more precise, the Atkinson index includes the inequality aversion parameter e. A low level of aversion is when $e = 0.5$, and a relatively high one when $e = 1.0$. Even higher aversion parameters tend to give results close to perfect inequality (i.e., index value of 1). Both indices are between 0 and 1 but we rescaled them to be between 0 and 100.

[42] This is based on the assumption that all energy savings feed into savings. Therefore, the estimated impact on the wealth distribution should be regarded as the effect on 'consumption equivalent' wealth.

efficient home and/or have not undertaken recent home improvements (i.e., for whom Home improvementi,t and/or Energy efficiencyi,t equals zero in Eq. (5.6.7)) are provided with an energy-efficient home. Policy 2 extends this support to all households below the median income. Policy 3 offers an energy-efficient home to all households, eliminating any differences in the level of energy efficiency across the income distribution.

Policy 1 reduces inequality only slightly (compared to the status quo), but does lead to a significant reduction in poverty (Atkinson indices). Importantly, this policy only captures 17 captures of the overall potential CO2 emission reductions, leaving 83 percent unrealized. Under Policy 2 the inequality-reducing effects become stronger, yet 63 percent of the potential CO2 emission reductions remain unrealized, as these benefits stem from the upper part of the income distribution. Policy 3 performs best in terms of inequality and poverty reduction and captures the most CO2 benefits.[43] Paradoxically, if the objective is to achieve climate goals effectively, our results suggest that policymakers should also incentivize households with above-median incomes. This does not necessarily imply that we should *subsidize* wealthy households. Rather, our results indicate that we need to consider how to *incentivize* wealthy households (for example, through taxes or higher prices), as these households are typically the most brown.

Although the exact costs of these policies are complex to estimate, Panel C provides an indication of their potential magnitude. Assuming that obtaining an energy-efficient house (through sorting or home improvements or a combination of both) costs around 6,000 euro, with a lower bound of 3,000 euro and an upper bound of 9,000 euro [44], the cost ranges between 14 and 42 billion euro which is about 2.2 percent to 5.5 percent of GDP in 2018. Under all policy scenarios, the costs substantially exceed the monetary value of the associated CO2 emission reductions – which aligns with the conclusions

[43] Inequality and poverty decline since there are many households in the lower part of the upper quartile of the income distribution who did not improve the energy-efficient of their home yet. As a result, this policy scenario reduces inequality within the upper quartile, and hence leads to the largest reduction in inequality overall.

[44] Fowlie et al. (2018) report a retrofit cost of 4,585 dollars. Aydin and Brounen (2016) find that house prices in the Netherlands are 5,000 euro higher for homes with an A-energy label compared to those with a D-label.

of Fowlie et al. (2018).[45] To compare the cost-effectiveness of different policies, we normalize their impact by the investment cost. When expressed per billion euros invested, Policy 1 reduces the Atkinson index by 0.11 percent and achieves 0.13 billion euro in CO2 emission reductions. Policy 2 reduces inequality by 0.17 percent and achieves 0.16 billion euro in CO2 emission reductions, while Policy 3 achieves the largest reductions on both fronts (0.20 percent and 0.25 billion euro, respectively). This confirms our earlier conclusion that broader policies are more effective in both inequality reduction and emission savings relative to their cost.

5.8 Conclusion

The transition to a green economy requires fundamental changes in the way in which firms produce, but also in the way in which households live. This paper sheds light on the critical intersection between household income, housing, and the transition to a green economy. Our results reveal that high-income households are more likely to make energy-efficient home improvements and tend to sort into energy-efficient homes. Both of these effects accumulate to 17 percent of median net wealth over a 15-year horizon. Most of this effect, about 65 percent, is not due to actively improving the energy efficiency of the existing home, but by presorting into energy-efficient homes. Although many policies focus on the intensive margin, there is real potential to help the energy transition through the extensive (supply side) margin as well via, for example, stricter building codes.

While high-income households contribute to a more sustainable living environment, the rate at which households become green is not equally distributed throughout society. Even though the potential energy savings for households are relatively higher at the bottom of the wealth distribution, these households are less likely to realize these benefits – which may increase wealth inequality. However, alleviating poverty and

[45] While changes in economic conditions or technological (leading to lower costs) or the use of a higher social cost of carbon could render some of these policies worthwhile from an environmental perspective (i.e., not accounting for poverty or inequality considerations), they are currently not cost-efficient.

sheltering households below the median income against higher energy expenditures comes at the cost of less effectively reducing CO2 emissions. Specifically, almost 63 percent of the potential CO2 benefits are emitted by households in the above median income group.

Although our study emphasizes the economic relevance of sustainable living choices, it also underscores the importance of recognizing the unequal distribution of efforts toward sustainability and the subsequent impact on the accumulation and distribution of wealth. As societies make efforts to mitigate climate change, this underscores the importance of designing policies that not only promote climate goals but also ensure an equitable transition to a green economy.

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Appendix

5.10 Household Optimization Problem

Households maximize lifetime utility subject to their budget constraints. In the first period, households spend their income on purchasing housing capital and investing in energy efficiency, and save any remaining income. In the second period, households purchase energy and spend the remainder of their savings, including the resale value of their housing capital, on the purchase of the non-durable consumption good.

$$\max_{c_{i,t+1}, e_{i,t+1}, x_{i,t}, H_{i,t+1}} U(c_{i,t+1}, e_{i,t+1}, H_{i,t+1}) = \left[\theta \left(H_{i,t+1}^{\rho} \cdot e_{i,t+1}^{1-\rho}\right)^{\eta} + (1-\theta) c_{i,t+1}^{\eta}\right]^{1/\eta} \tag{5.10.8}$$

$$\begin{aligned} s.t. \quad (y_i + A_{i,t}) &\leq \left(p + \frac{1}{2} x_{i,t}^2\right) H_{i,t} + S_{i,t} \\ c_{i,t+1} &\leq (1+r) S_{i,t} + \left(p - (1 - x_{i,t}^{\phi}) \cdot e_{i,t+1} \cdot q\right) \cdot H_{i,t} \\ c_{i,t+1}, e_{i,t+1}, x_{i,t}, H_{i,t} &\geq 0 \end{aligned}$$

The equilibrium is characterized by a system of equations. Specifically, the optimal investment in energy efficiency for a given household i in period t is given by

$$x_{i,t}^{*} = \left(\frac{\phi \cdot e_{i,t+1}^{*} \cdot q}{(1+r)}\right)^{\frac{1}{2-\phi}} \tag{5.10.9}$$

which increases in the price of energy, q, as well as the amount of energy consumed, $e_{i,t+1}$.

The optimal demand for energy and housing are implicitly defined by

$$e^*_{i,t+1} = \left[\frac{(1-\theta)}{\theta} \cdot \frac{q \cdot (1 - x^{*\phi}_{i,t})}{(1-\rho)} \cdot \frac{c^{*\eta-1}_{i,t+1}}{H^{*\rho-1}_{i,t} \left(H^{*\rho}_{i,t} \cdot e^{*(1-\rho)}_{i,t+1} \right)^{\eta-1}} \right]^{-\frac{1}{\rho}} \tag{5.10.10}$$

$$H^*_{i,t+1} = \left[\frac{(1-\theta)}{\theta} \cdot \frac{(1+r)\left(p + \frac{1}{2}x^{*2}_{i,t}\right) - \left(p - (1 - x^{*\phi}_{i,t}) \cdot e^*_{i,t+1} \cdot q\right)}{\rho} \cdot \frac{c^{*\eta-1}_{i,t+1}}{e^{*(1-\rho)}_{i,t} \left(H^{*\rho}_{i,t} \cdot e^{*(1-\rho)}_{i,t+1} \right)^{\eta-1}} \right]^{\frac{1}{\rho-1}} \tag{5.10.11}$$

The demand for the consumption good follows from the time $t+1$-spending constraint:

$$c^*_{i,t} = (1+r)\left((y_i + A_{i,t}) - \left(p + \frac{1}{2}x^{*2}_{i,t}\right) H^*_{i,t}\right) + \left(p - (1 - x^{*\phi}_{i,t}) \cdot e^*_{i,t+1} \cdot q\right) \cdot H^*_{i,t}. \tag{5.10.12}$$

5.11 The 2006 WoON-survey

We assess the robustness of our results at different spatial scales using the WoON 2006 survey, to which there are 64,005 respondents. The 2006 dataset was the first edition of the survey in its current forum and is particularly useful as it contains detailed information about location (zip code). It is the only wave that had such detailed location information in the public use file. This survey further contains both household income and energy expenditures from administrative sources and proxies for home improvement and energy efficiency of the home.

Households were surveyed between August 2005 - March 2006. We focus on the respondents for whom all variables of interest are available, which gives us a sample of 54,173 respondents. Table 5.11.6 provides summary statistics. The cross-sectional dataset consists of households living in owner-occupied housing (55.4 percent) as well as rental housing, where we distinguish between the free rental sector (6.0 percent) and social housing (38.6 percent).

In the 2006-survey, our main variables of interest have slightly different definitions. Specifically, the home improvements-variable is a binary variable that indicates whether a household has done insulation or energy saving facilities (also by order of the landlord) such as double glazing, roller shutters, floor insulation, the installation of an HR boiler or water saving measures in the past 12 months. The energy efficiency-variable is a binary variable that indicates whether the house has double glazing. Most of the households in our sample live in energy-efficient homes (90.3 percent). Only 15.2 percent of households in our sample have made improvements in energy efficiency at home 12 months prior to the survey.

The main independent variable of interest is households' disposable income, which again comes from tax registry data (merged by Statistics Netherlands). Within this wave, the mean household income is equal to 31,140 euro, and the median is 27,116 euro.

Variable	Mean	SD	Min	Max
Energy efficiency & home improvements				
Energy efficiency (double glass, living room)	0.903	0.297		
Home improvement (insulation, last 12 months)	0.152	0.359		
Household Characteristics				
Spendable household inc.(euro)	31,140	27,458	142	1,757,024
Age	51	17	18	103
Young child	0.476	0.265		
Female	0.549	0.498		
Higher education	0.263	0.440		
House Characteristics				
House size (sq. mtr.)	123	78	6	935
Construction $<$ 1945	0.183	0.387		
Construction 1945-1959	0.121	0.326		
Construction 1960-1969	0.147	0.355		
Construction 1970-1979	0.194	0.396		
Construction 1980-1989	0.156	0.362		
Construction 1990-1999	0.137	0.344		
Construction $>$ 1999	0.062	0.241		
Single-standing	0.134	0.340		
Two under one roof	0.115	0.318		
Corner	0.115	0.318		
Row	0.191	0.357		
Flat/apartment 1990-1999	0.312	0.168		
Other	0.095	0.105		
Sector				
Social housing	0.386	0.482		
Free-rental sector	0.060	0.271		
Owner-occupied	0.554	0.497		
Energy Expenditures				
Annual gas expenditures (euro)	1,054	517	138	5,084
as part of income	0.044	0.039	0.002	1.866
Annual electricity expenditures (euro)	745	399	83	3,484
as part of income	0.029	0.026	0.001	1.513
Annual water expenditures (euro)	176	55	69	709
as part of income	0.007	0.009	0.001	1.732
Utility expenditures (euro)	1,976	770	324	8,470
as part of income	0.080	0.565	0.008	1.962
Heating: own boiler	0.805	0.396		
Heating: block/district/city	0.111	0.315		
Heating: heater	0.072	0.259		
Heating: other	0.011	0.103		
Number of persons in hh	2.959	1.321	1	27
Robustness				
Partner	0.628	0.483		
Instrumental variables				
Divorce	0.009	0.093		
Marriage	0.021	0.144		

Note: Based on 54,173 observations, from the WoON-survey (2006). We restrict all types of energy expenditures as a share of income to be at most equal to two.

Table 5.11.6: Home improvement, energy efficiency, and energy expenditures (2006).

Table 5.11.7: Home Improvements and Energy Efficiency - Baseline Estimates (2006)

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	Home Improvement			Energy Efficiency				
	Baseline	Sector	Owner-Occupied	Baseline	Sector	Social rent	Free rent	Owner-Occupied
Income (log)	0.0268***	0.0117**	0.0160**	0.0331***	0.0303***	0.0191***	0.0379*	0.0345***
	(0.004)	(0.005)	(0.006)	(0.004)	(0.004)	(0.006)	(0.020)	(0.005)
Social rent		-0.0552***			0.0046			
		(0.007)			(0.006)			
Free rent		-0.0664***			-0.1020***			
		(0.008)			(0.009)			
Household Char.	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
House Char.	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Location FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Observations	54,173	54,173	30,004	54,173	54,173	19,831	4,338	30,004
Adjusted R-squared	0.048	0.052	0.057	0.120	0.128	0.090	0.191	0.121

Note: Estimation results for Eq. (5.5.5) (columns 1–3) and Eq. (5.5.6) (columns 5–8), based on the WoON-survey (2006). We estimate both equations with OLS and include location fixed effects based on ZIP-codes. Standard errors are clustered at the municipality-level. *** $p<0.01$, ** $p<0.05$, * $p<0.1$.

Table 5.11.8: Different Spatial Scale of Fixed Effects (2006)

	(1)	(2)	(3)	(4)	(5)	(6)
	Home Improvements			Energy Efficiency		
Spatial Scale	COROP	MUNICIP.	ZIPCODE	COROP	MUNICIP.	ZIPCODE
Income (log)	0.0288***	0.0285***	0.0268***	0.0285***	0.0279***	0.0331***
	(0.004)	(0.004)	(0.004)	(0.004)	(0.004)	(0.004)
Household Characteristics	Yes	Yes	Yes	Yes	Yes	Yes
House Characteristics	Yes	Yes	Yes	Yes	Yes	Yes
Location FE	Yes	Yes	Yes	Yes	Yes	Yes
Observations	54,173	54,173	54,173	54,173	54,173	54,173
Adjusted R-squared	0.037	0.039	0.048	0.101	0.104	0.120

Note: Estimation results for Eq. (5.5.5) (columns 1-3) and Eq. (5.5.6) (columns 4-6), based on the WoON-survey (2006). We estimate the equations with OLS using (i) COROP, (ii) municipality and (iii) ZIP-code level fixed effects. Standard errors are clustered at the municipality-level, *** $p<0.01$, ** $p<0.05$, * $p<0.1$.

5.12 Heterogeneity tests based on the WoON-survey (2018)

Table 5.12.9: Different types of home improvements (2018)

VARIABLES	(1) Home Improv.	(2) Double Glass	(3) Insulation	(4) Solar	(5) Boiler	(6) Other
Income (log)	0.0698***	0.0330***	0.0404***	0.0241***	0.0428***	0.0264***
	(0.005)	(0.004)	(0.003)	(0.002)	(0.005)	(0.003)
Household Characteristics	Yes	Yes	Yes	Yes	Yes	Yes
House Characteristics	Yes	Yes	Yes	Yes	Yes	Yes
Location FE	Yes	Yes	Yes	Yes	Yes	Yes
Observations	56,283	56,283	56,283	56,283	56,283	56,283
Adjusted R-squared	0.091	0.064	0.097	0.044	0.055	0.014

Note: Estimation results for Eq. (5.5.5) for various types of home improvement, based on the WoON-survey (2018). We estimate the equation with OLS, and include location fixed effects. Standard errors are clustered at the COROP-level, *** p<0.01, ** p<0.05, * p<0.1.

Table 5.12.10: Energy Efficiency: Energy Label and Energy Index (2018)

VARIABLES	(1) Energy Label (temp.)	(2) Energy Label (fin.)	(3) Energy Index
Income (log)	0.0581***	0.0409***	-0.0300***
	(0.008)	(0.007)	(0.007)
Household Characteristics	Yes	Yes	Yes
House Characteristics	Yes	Yes	Yes
Construction Year	No	No	No
Location FE	Yes	Yes	Yes
Observations	54,170	22,789	16,855
Adjusted R-squared	0.064	0.039	0.039

Note: Estimation results for Eq. (5.5.6), based on the WoON-survey (2018). We use (i) temporary energy labels (column 1), (ii) final energy labels (column 2), and (iii) the energy index – which is inversely related to energy labels – (column 3) as proxies for energy efficiency. We estimate the relation without the inclusion of construction year as a control variable. All regressions include location fixed effects. Standard errors are clustered at the COROP-level. *** $p<0.01$, ** $p<0.05$, * $p<0.1$.

5.13 Reasons for Home Improvement, WoON (2018)

Table 5.13.11: Reasons for Doing and not Doing Home Improvements

VARIABLES	Observations	Mean	Std. Dev.
Necessary due to maintenance (1A)	23,485	0.426	0.494
Investment pays off (1B)	23,485	0.242	0.428
Make the home more pleasant (1C)	23,485	0.204	0.403
Environmental considerations (1D)	23,485	0.064	0.244
Agreed in homeowner's association (1E)	23,485	0.012	0.110
Enhance marketability of the home (1F)	23,485	0.011	0.106
Other reasons (1G)	23,485	0.0401	0.197

Panel A. Reasons for undertaking energy efficiency-enhancing home improvements.
Note: Based on Dutch survey data (WoON-survey) from 2018.

VARIABLES	Observations	Mean	Std. Dev.
Home is already energy efficient (2A)	11,310	0.384	0.486
Outside of my budget (2B)	11,310	0.167	0.373
Savings are insufficient (2C)	11,310	0.124	0.329
Don't know what the possibilities are (2D)	11,310	0.055	0.227
Don't want to renovate (2E)	11,310	0.069	0.253
Homeowner's association doesn't want this (2F)	11,310	0.020	0.141
Didn't get to it yet (2G)	11,310	0.224	0.417
Planning to move (2H)	11,310	0.060	0.238
Others (2I)	11,310	0.131	0.338

Panel B. Reasons for not undertaking energy efficiency-enhancing home improvements.
Note: Based on the WoON-survey (2018).

Table 5.13.12: Reasons for Undertaking Home Improvements (regression results)

VARIABLES	(1) 1A	(2) 1B	(3) 1C	(4) 1D	(5) 1E	(6) 1F	(7) 1G
Income (log)	-0.0451***	0.0012	0.0212***	0.0266***	0.0026*	-0.0018	-0.0048
	(0.011)	(0.008)	(0.006)	(0.004)	(0.001)	(0.002)	(0.004)
Household Characteristics	Yes	Yes	Yes	Yes	Yes	Yes	Yes
House Characteristics	Yes	Yes	Yes	Yes	Yes	Yes	Yes
ZIP-code FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Observations	23,104	23,104	23,104	23,104	23,104	23,104	23,104
Adjusted R-squared	0.039	0.028	0.033	0.032	0.109	0.002	0.034

Panel A. Reasons for undertaking energy efficiency enhancing home improvements.
Note: Estimation results for the various reasons to undertake home improvements, based on the WoON-survey (2018). We estimate the equation with OLS, and include location fixed effects. Standard errors are clustered at the COROP-level, *** $p<0.01$, ** $p<0.05$, * $p<0.1$.

Table 5.13.13: Reasons for Not Undertaking Home Improvements (regressions results)

VARIABLES	(1) 2A	(2) 2B	(3) 2C	(4) 2D	(5) 2E	(6) 2F	(7) 2G	(8) 2H	(9) 2I
Income (log)	0.0340***	-0.0980***	0.0176***	-0.0008	-0.0024	0.0013	0.0346***	0.0118***	0.0006
	(0.009)	(0.008)	(0.006)	(0.005)	(0.005)	(0.003)	(0.008)	(0.004)	(0.007)
Household Characteristics	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
House Characteristics	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
ZIP-code FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Observations	11,109	11,109	11,109	11,109	11,109	11,109	11,109	11,109	11,109
Adjusted R-squared	0.134	0.059	0.021	0.012	0.020	0.110	0.059	0.006	0.017

Panel B. Reasons for not undertaking energy efficiency enhancing home improvements.

Note: Estimation results for the various reasons not to undertake home improvements, based on the WoON-survey (2018). We estimate the equation with OLS, and include location fixed effects. Standard errors are clustered at the COROP-level, *** $p<0.01$, ** $p<0.05$, * $p<0.1$.

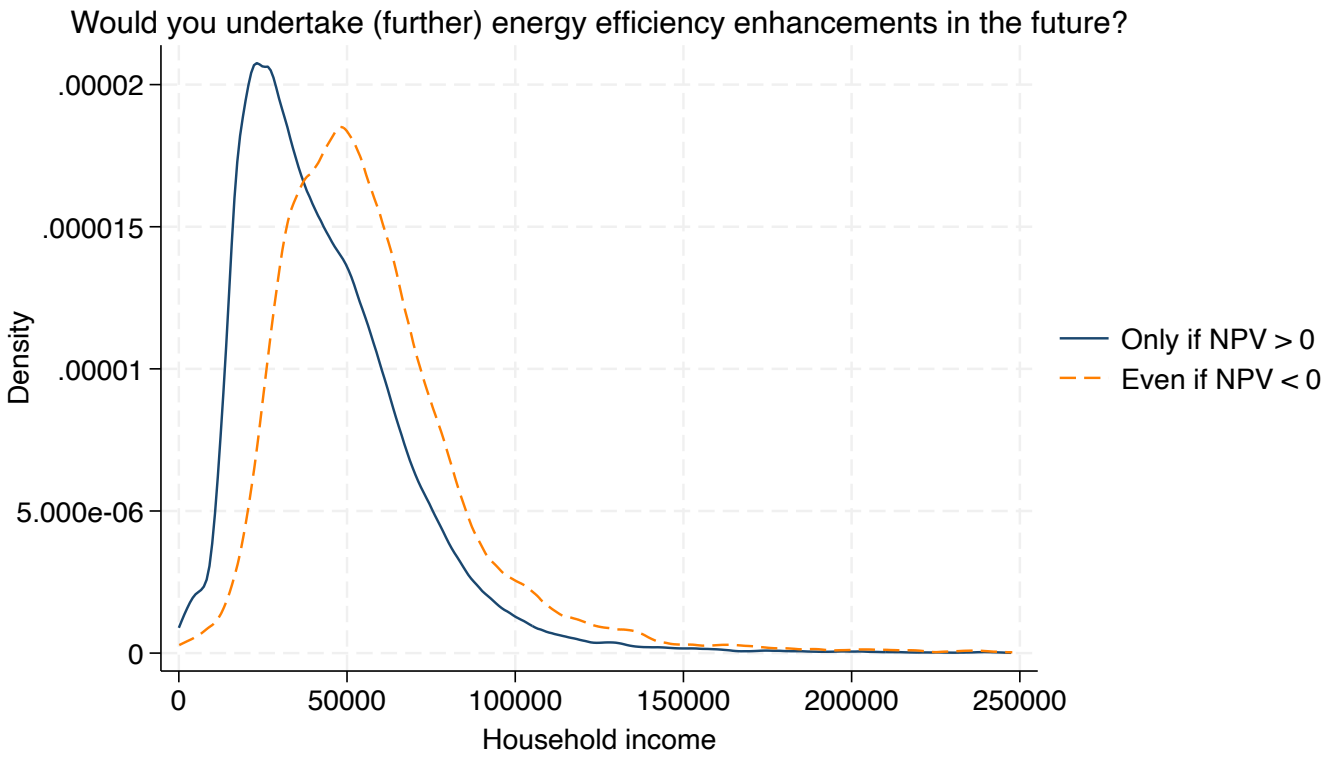


Figure 5.13.3: Distribution of responses by household income on the conditions for undertaking (further) energy efficiency improvements in the future. Households with income below 0 or above 250,000 euro are excluded from the density plot.

5.14 Home Improvements, Subsidies, and Wealth (2018)

Table 5.14.14: Home improvement and Subsidies (2018)

Income	Home Improv.	Doub. Glass	Insulation	Solar Pan.	Heat. Boiler	Other Improv.
1st Quartile	0.087	0.098	0.129	0.472	0.068	0.122
2nd Quartile	0.119	0.129	0.182	0.506	0.091	0.125
3rd Quartile	0.145	0.147	0.187	0.497	0.109	0.162
4th Quartile	0.164	0.168	0.204	0.492	0.130	0.176
Total	**0.142**	**0.147**	**0.189**	**0.495**	**0.110**	**0.158**

Note: Based on 56,283 observations from the WoON-survey (2018). We present the percentage of households that received a subsidy for doing a (specific type of) home improvement, conditional on having undertaken that improvement. The threshold are as follows: 1^{st} Quartile $<$25k euro, 2^{nd} Quartile 25k-38k euro, 3^{rd} Quartile 38k-55k euro, 4^{th} Quartile $>$55k euro.

Table 5.14.15: Home improvement and Subsidies (2018)

VARIABLES	(1) Home Improv.	(2) Double Glass	(3) Insulation	(4) Solar	(5) Boiler	(6) Other
Income (log)	0.1420***	0.0670***	0.0545***	0.0221***	0.0942***	0.0308***
	(0.007)	(0.004)	(0.004)	(0.002)	(0.005)	(0.002)
Subsidy (yes/no)	0.4316***	0.2031***	0.2714***	0.5155***	0.1124***	0.1011***
	(0.008)	(0.012)	(0.026)	(0.025)	(0.008)	(0.007)
Household Characteristics	Yes	Yes	Yes	Yes	Yes	Yes
House Characteristics	Yes	Yes	Yes	Yes	Yes	Yes
ZIP-code FE	Yes	Yes	Yes	Yes	Yes	Yes
Observations	46,466	46,466	46,466	46,466	46,466	46,466
Adjusted R-squared	0.235	0.110	0.158	0.277	0.100	0.032

Note: Estimation results for Eq. (5.5.5) for various types of home improvement, based on the WoON-survey (2018). We estimate the equation with OLS, and include location fixed effects. Standard errors are clustered at the COROP-level, *** p<0.01, ** p<0.05, * p<0.1.

Table 5.14.16: Effect of Income vs Wealth (2018)

VARIABLES	(1) Home Improv.	(2) Energy Eff.	(3) Home Improv.	(4) Energy Eff.
Income (log)	0.0595***	0.0420***	0.0711***	0.0543***
	(0.006)	(0.006)	(0.006)	(0.007)
Total Assets	0.0094***	0.0109***		
	(0.001)	(0.002)		
Net Wealth			0.0144***	0.0252**
			(0.005)	(0.009)
Household Characteristics	Yes	Yes	Yes	Yes
House Characteristics	Yes	Yes	Yes	Yes
Location FE	Yes	Yes	Yes	Yes
Observations	55,619	53,528	55,418	53,378
Adjusted R-squared	0.093	0.068	0.091	0.065

Note: Estimation results for Eq. (5.5.5) and Eq. (5.5.6), based on the WoON-survey (2018). We include wealth as an explanatory variable, using total assets (columns 1-2) and net wealth (column 3-4) as proxy. Results for Eq. (5.5.5) are reported in columns 1 and 3, and for Eq. (5.5.6) in columns 2 and 4. We estimate the equation with OLS, and include location fixed effects. Standard errors are clustered at the COROP-level, *** $p<0.01$, ** $p<0.05$, * $p<0.1$.

5.15 The COVID-19 Pandemic, WoON (2021)

Variable	Mean	SD	Min	Max
Household Characteristics				
Spendable household inc.(euro)	50,438	48,038	32	1,306,182
Total wealth	321,770	343,135	0	2,497,365
Net wealth	206,457	285,328	-198,084	1,997,481
Age 17-24	0.025	0.155		
Age 25-34	0.138	0.345		
Age 35-44	0.147	0.354		
Age 45-54	0.176	0.381		
Age 55-64	0.198	0.399		
Age 65-74	0.184	0.388		
Age 75+	0.132	0.338		
Young child	0.081	0.272		
Partner	0.606	0.489		
Higher education	0.378	0.485		
House Characteristics				
House size (sq. mtr)	125.079	84.789	10.000	2,700.000
Construction $<$ 1945	0.184	0.387		
Construction 1945-1959	0.079	0.270		
Construction 1960-1969	0.120	0.325		
Construction 1970 - 1979	0.161	0.368		
Construction 1980 - 1989	0.145	0.352		
Construction 1990 - 1999	0.126	0.332		
Construction 2000 - 2009	0.101	0.301		
Construction $>$ 2010	0.084	0.277		
Single-standing	0.160	0.367		
Two under one roof	0.138	0.345		
Corner	0.126	0.332		
Row and other	0.281	0.449		
Flat	0.295	0.456		
Sector				
Social	0.229	0.421		
Rent	0.108	0.311		
Occupied	0.662	0.473		
Energy expenditures				
Annual gas expenditures (euro)	1,143	547	233	6,331
as part of income	0.0317	0.0450	0.002	1.916
Annual electricity expenditures (euro)	951	335	309	2,820
as part of income	0.026	0.037	0.001	1.988
Annual water expenditures (euro)	188	57	99	666
as part of income	0.005	0.008	0.000	0.488
Utility expenditures (euro)	2,282	780	713	8,427
as part of income	0.062	0.064	0.0014	1.942
Heating type	1.855	1.653	1.000	8.000
Number of persons in hh	2.221	1.174	1.000	5.000

Note: Based on 38,814 observations from the WoON-survey (2021). For for net wealth, we have 38,050 observations. We restrict all energy expenditures as a share of income to be at most equal to two. We have 8 dummies for the different heating types (central heating boiler, wood-burning heating device, pellet stove, gas heater, heat pump, block/district heating, city heating, other). In our sample, 86% of respondents have a central heating boiler. The variable 'heating type' displays the average heating type.

Table 5.15.17: Household, house characteristics, and energy expenditures (2021)

Variable	Energy Eff.	A-Label	B-Label	C-Label	D-Label	E-Label	F-Label	G-Label
Mean (Overall)	0.448	0.277	0.171	0.264	0.134	0.072	0.047	0.036
Social	0.455	0.263	0.115	0.296	0.150	0.058	0.026	0.014
Rent	0.413	0.275	0.138	0.223	0.138	0.094	0.066	0.067
Owner-occupied	0.451	0.288	0.163	0.251	0.121	0.076	0.058	0.044
Variable	Home Improv.	Glass	Insulation	Solar	Boiler	Heat. Pump	Other	
Mean (Overall	0.526	0.173	0.143	0.153	0.288	0.011	0.087	
Social	0.474	0.199	0.146	0.115	0.270	0.008	0.048	
Rent	0.329	0.101	0.053	0.042	0.210	0.007	0.041	
Owner-occupied	0.576	0.176	0.157	0.185	0.308	0.013	0.108	

Note: Based on 38,814 observations from WoON-survey (2021). *Home improvements*-variable is a binary variable equal to 1 if a household has undertaken at least one type of home improvement measure in the last 5 years (double glazing, roof, wall or floor insulation, the installation of solar panels, or the installation of boiler panels, or other energy-saving facilities), and zero otherwise. *Energy efficiency*-variable is a binary variable based on the energy label of the house and equal to 1 if a household lives in a house with an A or B energy label, and zero otherwise. Energy labels range from *A* to *G*, with *A* being the most energy-efficient, *G* the least efficient.

Table 5.15.18: Energy efficiency and home improvements (2021)

Table 5.15.19: Replication Baseline Results (2021)

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	Home Improvement			Energy Efficiency				
	Baseline	Sector	Owner-Occupied	Baseline	Sector	Social rent	Free rent	Owner-Occupied
Income (log)	0.0514***	0.0448***	0.0547***	0.0351***	0.0545***	0.0422***	0.0913***	0.0453***
	(0.005)	(0.006)	(0.006)	(0.009)	(0.008)	(0.010)	(0.014)	(0.015)
Social		-0.0092			0.0779***			
		(0.009)			(0.016)			
Rent		-0.1271***			0.0124			
		(0.008)			(0.016)			
Household Characteristics	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
House Characteristics	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
ZIP-code FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Observations	38,814	38,814	25,699	22,862	22,862	8,551	2,790	11,521
Adjusted R-squared	0.083	0.088	0.075	0.030	0.033	0.034	0.056	0.058

Note: Estimation results for Eq. (5.5.5) (columns 1–3) and Eq. (5.5.6) (columns 4–8), based on the WoON-survey (2021). We estimate both equations with OLS, and include location fixed effects. Standard errors are clustered at the COROP-level, *** p<0.01, ** p<0.05, * p<0.1.

5.16 Energy Expenditure Regressions, WoON (2018, 2021)

Table 5.16.20: Heterogeneity: Energy expenditure regressions (2018)

VARIABLES	(1) Utility/Income	(2) Utility/Income	(3) Utility/Income	(4) Utility/Income
Home improvements	-0.0047***		-0.0049***	
	(0.001)		(0.001)	
Double Glass		-0.0004		-0.0005
		(0.001)		(0.001)
Insulation		-0.0022***		-0.0031***
		(0.001)		(0.001)
Solar		-0.0071***		-0.0066***
		(0.001)		(0.001)
Heating		-0.0017***		-0.0016***
		(0.001)		(0.001)
Other		-0.0031***		-0.0031***
		(0.001)		(0.001)
Energy Efficiency	-0.0088***	-0.0086***		
	(0.001)	(0.001)		
A-Label			-0.0161***	-0.0156***
			(0.002)	(0.002)
B-Label			-0.0141***	-0.0143***
			(0.002)	(0.002)
C-Label			-0.0100***	-0.0101***
			(0.001)	(0.002)
D-Label			-0.0042***	-0.0040***
			(0.001)	(0.001)
E-Label			-0.0050*	-0.0050*
			(0.003)	(0.003)
F-Label			-0.0047***	-0.0047***
			(0.002)	(0.002)
Household Characteristics	Yes	Yes	Yes	Yes
House Characteristics	Yes	Yes	Yes	Yes
Location FE	Yes	Yes	Yes	Yes
Observations	53,822	53,822	53,822	53,822
Adjusted R-squared	0.002	0.001	0.002	0.001

Note: Estimation results for Eq. (5.6.7) for various types of energy expenditure, based on the WoON-survey (2018). We estimate the equation with OLS, and include location fixed effects. Energy label F is the reference category for energy labels. The home improvements are not mutually exclusive and thus do not have a reference category. Standard errors are clustered at the COROP-level, *** $p<0.01$, ** $p<0.05$, * $p<0.1$.

Table 5.16.21: Robustness: Energy expenditure regressions (2018, 2021)

VARIABLES	(1) WoOn-2021	(2) Quantile	(3) Interaction	(4) Other home impr.
Home improvements	-0.0018***	-0.0087***	-0.0052***	-0.0040***
	(0.0005)	(0.0010)	(0.0007)	(0.0005)
Energy efficiency	-0.0079***	-0.0178***	-0.0097***	-0.0091***
	(0.0006)	(0.0009)	(0.0010)	(0.0008)
Home impr.x Energy eff.			0.0018	
			(0.0012)	
Dormer or roof structure				0.0022**
				(0.0010)
Extension or sun-room				0.0034***
				(0.0009)
Kitchen or bathroom				0.0022***
				(0.0007)
Adjusted house plan				0.0032***
				(0.0009)
Household Characteristics	Yes	Yes	Yes	Yes
House Characteristics	Yes	Yes	Yes	Yes
Location FE	Yes	Yes	Yes	Yes
Observations	22,723	53,782	53,782	53,782
Adjusted R-squared	0.115	0.143	0.108	0.109

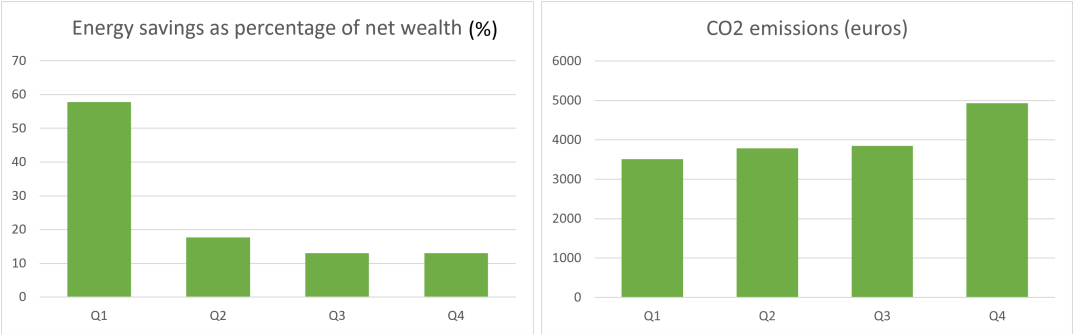
Note: Robustness tests for Eq. (5.6.7). We include location fixed effects. In column 2 we look at the 95% quantile for utility expenditures relative to income. Columns 5 and 6 are based on the estimation of a system of equations, in which income, home improvements, energy efficiency and utility expenditures are used as dependent variables. For the quantile regression, we report the Pseudo-R^2. Standard errors are clustered at the COROP level, *** p<0.01, ** p<0.05, * p<0.1.

Table 5.16.22: Present value of average energy savings (2018)

Investment horizon		$\rho = 0.02$	$\rho = 0.05$	$\rho = 0.08$
10-year horizon	in euro	5,273	4,533	3,939
	as % of median wealth	2.8	2.4	2.1
	as % of median net wealth	14.8	12.7	11.1
15-year horizon	in euro	7,543	6,093	5,024
	as % of median wealth	3.9	3.2	2.6
	as % of median net wealth	21.2	17.1	14.1
20-year horizon	in euro	9,598	7,315	5,763
	as % of median wealth	5.0	3.8	3.0
	as % of median net wealth	27.0	20.6	16.2

Note: Based the WoON-survey (2018). The real interest rate is based on a nominal interest rate of 4, 7 and 10% respectively, and an inflation rate of 2%.

Figure 5.16.4: The energy-efficiency paradox (2021)



Note: The left panel displays energy savings in euro as a percentage of net wealth, by income quartile. The right panel displays the current carbon footprint of households by income quartile, as measured by the CO2 emissions associated with their energy consumption.

Summary in English

This dissertation examines the macro-financial implications of climate change. I study how market incentives and financing frictions shape households' response to climate change, through adaptation and mitigation, along with the resulting distributional effects and implications for political support for climate policies. I also examine how investors respond to firms' efforts to mitigate climate transition risks and the associated pricing implications.

Due to insufficient progress on climate change mitigation, adaptation is increasingly critical to reduce the economic losses associated with extreme weather events. The second chapter of this dissertation examines how financial incentives shape households' private adaptation efforts. More concretely, I study the direct effects of climate change on housing and financial markets, the efficiency of household adaptation, and the role of financial constraints in limiting adaptive efforts. I develop a general equilibrium model with overlapping generations, where climate risks damage housing and degrade land. Climate change affects house prices along two channels: expected future damages reduce house prices due to weakened demand for houses exposed to physical climate risk, while the scarcity of land increases prices by raising households' willingness to pay for housing. If households are sufficiently risk-averse with respect to their housing consumption, the supply effect dominates, causing house prices to rise in the long run.

Households endogenously adapt to climate change and are guided by price signals in this effort, given that prices reflect the value at risk of climate impacts. In frictionless markets, price signals lead to efficient adaptation, as households internalize the inter-

generational benefits of their adaptation efforts. However, credit-constrained households have weaker incentives to adapt to climate change, indicating that pricing alone may be insufficient. Unequal adaptation reinforces wealth inequality and leads to a further reduction in future habitat. As a result, households become endogenously more constrained, which causes the private adaptation gap to widen over time. I show that a societal shift from constrained homeownership to a rental model with unconstrained owners could lead to more efficient adaptation.

Economic polarization tightens financial conditions, undermining private adaptation. Public intervention can alleviate this by preserving habitable land, but investment in protective infrastructure relies on political support. The third chapter of this dissertation study the evolution of voter support for public adaptation when political preferences are shaped by rising climate risk and economic inequality.

Political support for tax-funded intervention to preserve habitable land evolves over time when households differ in age, income and political beliefs. Support for public adaptation is initially low, rising as climate risk increases. We show that the political equilibrium experiences a tipping point in response to habitat loss if beliefs are not too dispersed, leading to a shift towards a more active adaptation policy. Rising inequality may induce another tipping point, as lower income households stand to gain more from public adaptation. However, the policy impact depends on the balance between income differences and heterogeneous political beliefs. This highlights the importance of redistributive policies to effectively contain the damages from climate change.

As adaptation alone cannot fully shield economies from climate-related losses, the transition to a green economy is essential. The fourth chapter of this dissertation studies whether investors price climate transition risk in the corporate bond market. We take a forward-looking approach by incorporating firms' green innovation alongside their past and current carbon emissions. We find evidence of a positive transition risk premium, which rises in a firm's emission intensity. This risk premium is significantly lower for emission-intensive firms that engage in green innovation, suggesting that investors value companies' efforts to mitigate climate change.

While investors divest from emission intensive firms, our findings suggest that those with greater risk-bearing capacity play a crucial role in the green transition by channeling capital toward emission-intensive firms that actively invest in green innovation. Using confidential bond-level holdings data, we show that European institutional investors, particularly mutual funds, have a higher demand for bonds from emission-intensive firms that engage in green innovation.

The green transition also calls for households to decrease energy consumption within their homes. The fifth chapter of this dissertation empirically examines the pace at which households transition to greener housing and its effects on the distribution of wealth and emissions. Using Dutch survey and administrative data, we find that low-income households are less likely to invest in energy efficiency, while higher-income households more often sort into more energy efficient homes. We show that energy savings are relatively larger for low-income households. Policies targeting low-income households could thus enhance equity. However, most potential emission reductions come from addressing higher-income households, who have a higher carbon footprint. This highlights a trade-off between reducing inequality and maximizing emission reductions.

Samenvatting

Dit proefschrift onderzoekt de macro-financiële implicaties van klimaatverandering. Ik onderzoek hoe markt- en financiële prikkels de reactie van huishoudens op klimaatverandering beïnvloeden, via zowel adaptatie als mitigatie, en analyseer de daaruit voortvloeiende verdelingseffecten en implicaties voor de politieke steun voor klimaatbeleid. Daarnaast onderzoek ik hoe beleggers reageren op de inspanningen van bedrijven om klimaattransitierisico's te beperken door middel van groene innovatie, en wat hiervan de prijsimplicaties zijn op financiële markten.

Door onvoldoende mitigatie wordt adaptatie een steeds belangrijker instrument om de economische schade van klimaatverandering te beperken. In het tweede hoofdstuk van dit proefschrift onderzoek ik hoe financiële prikkels klimaatadaptatie door huishoudens beïnvloeden. Ik bestudeer het directe effect van klimaatverandering op huizenprijzen, de efficiëntie van private adaptatie en de mate waarin financiële beperkingen private adaptatie verhinderen. Ik ontwikkel een algemeen-evenwichtsmodel met overlappende generaties, waarin klimaatrampen woningen beschadigen en leefbaar land doet afnemen. Klimaatrisico's beïnvloeden huizenprijzen via twee tegengestelde kanalen: enerzijds drukt de verwachte toekomstige schade de prijs doordat de vraag naar risicovolle locaties afneemt; anderzijds leidt de toenemende schaarste aan leefbaar land tot prijsstijgingen. Wanneer huishoudens voldoende risico-avers zijn ten aanzien van hun woningconsumptie, domineert het aanbodeffect en stijgen huizenprijzen op de lange termijn.

Huishoudens investeren in adaptatie en laten zich daarbij leiden door prijsprikkels die de waarde van toekomstig klimaatrisico weerspiegelen. In frictieloze markten lei-

den deze prikkels tot efficiënte adaptatie, omdat huishoudens de baten van hun adaptatiemaatregelen voor toekomstige generaties internaliseren. Echter, kredietbeperkte huishoudens hebben lagere prikkels om te investeren in klimaatadaptatie, wat erop wijst dat prijsmechanismen mogelijk onvoldoende zijn. Ongelijke adaptatie vergroot de vermogensongelijkheid en versnelt de degradatie van leefbaar land. Hierdoor raken steeds meer huishoudens kredietbeperkt, wat de private adaptatiekloof verder vergroot over de tijd. Ik laat zien dat het stimuleren van huren onder huishoudens met beperkte toegang tot krediet kan leiden tot efficiëntere klimaatadaptatie.

Economische polarisatie verslechtert financiële condities, waardoor private adaptatie onder druk komt te staan. Publieke interventie kan dit verhelpen, maar investeringen in beschermende infrastructuur zijn afhankelijk van politieke steun. Het derde hoofdstuk van dit proefschrift bestudeert de evolutie van politieke steun voor publieke adaptatie, waarbij politieke voorkeuren worden beïnvloed door toenemende klimaatrisico's en economische ongelijkheid.

De politieke steun voor door belastingen gefinancierde maatregelen om land bewoonbaar te houden ontwikkelt zich in de tijd, afhankelijk van leeftijd, inkomen en politieke overtuiginge van huishoudens. Aanvankelijk is de steun laag, maar deze neemt toe naarmate klimaatrisico's groter worden. Het politieke evenwicht kan een "tipping point" bereikt als gevolg van verlies aan leefgebied, mits poltieke overtuigingen niet te sterk uiteenlopen. Dit leidt tot een actiever adaptatiebeleid. Een stijgende ongelijkheid kan een tweede tipping point veroorzaken, omdat huishoudens met een lager inkomen meer afhankelijk zijn van publieke adaptatie. Het uiteindelijke beleidseffect hangt echter af van de verhouding tussen inkomensverschillen en verschillen in politieke overtui-gingen. Dit benadruk de noodzaak van herverdelingsbeleid in de strijd tegen klimaatverandering.

Aangezien adaptatie de economie niet volledig kan beschermen tegen klimaatgerelateerde schade, is een transitie naar een groene economie essentieel. Het vierde hoofdstuk van dit proefschrift onderzoekt of en hoe investeerders klimaattransitierisico beprijzen op de markt voor bedrijfsobligaties. We hanteren een vooruitziende benadering

door zowel de historische en huidige uitstoot van bedrijven als hun investeringen in groene innovatie mee te nemen. We vinden bewijs voor een positieve transitie-risicopremie, die toeneemt met de emissie-intensiteit van een bedrijf. Tegelijkertijd is deze premie aanzienlijk lager voor emissie-intensieve bedrijven die actief investeren in groene innovatie. Dit suggereert dat investeerders inspanningen om klimaatverandering te beperken positief waarderen in hun prijsstelling.

Hoewel veel investeerders desinvesteren uit emissie-intensieve bedrijven, laten onze resultaten zien dat investeerders met een grotere risicodraagkracht een cruciale rol spelen in de groene transitie door gericht kapitaal te alloceren naar emissie-intensieve bedrijven die actief investeren in groene innovatie. Op basis van confidentiële data over obligatiebezit laten we aan dat Europese institutionele investeerders, met name beleggingsfondsen, een grotere vraag hebben naar obligaties van emissie-intensieve bedrijven die groen innoveren.

De groene transitie vereist ook dat huishoudens hun energieverbruik verminderen. Het vijfde hoofdstuk van dit proefschrift onderzoekt empirisch de snelheid waarmee huishoudens hun woning verduurzamen en de effecten daarvan op de vermogensverdeling en emissies. Op basis van Nederlandse enquête- en administratieve data, laten we zien dat huishoudens met een laag inkomen minder geneigd zijn te investeren in energie-efficiëntie, terwijl huishoudens met een hoger inkomen vaker voor een efficiënte woningen kiezen bij verhuizing. We laten zien dat energiebesparingen relatief groter zijn voor huishoudens met een laag inkomen, wat impliceert dat beleid dat zich richt op huishoudens met een laag inkomen de vermogensongelijkheid kan verkleinen. Echter, het grootste emissie-reductiepotentieel ligt bij hogere inkomens, aangezien hun uitstoot het hoogst is. Dit wijst op een afruil tussen het verminderen van ongelijkheid en het maximaliseren van emissiereducties.

The Tinbergen Institute is the Institute for Economic Research, which was founded in 1987 by the Faculties of Economics and Econometrics of the Erasmus University Rotterdam, University of Amsterdam and Vrije Universiteit Amsterdam. The Institute is named after the late Professor Jan Tinbergen, Dutch Nobel Prize laureate in economics in 1969. The Tinbergen Institute is located in Amsterdam and Rotterdam. For a full list of PhD theses that appeared in the series we refer to List of PhD Theses – Tinbergen.nl. The following books recently appeared in the Tinbergen Institute Research Series:

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