Other Relevant Documents

Ghassane Benmir

LSE and PSL Research, November 1, 2022

This file contains the following documents:

1. My Personal Statement,
2. My Research Statement,
3. My Teaching Statement,
4. My Teaching Evaluations.
5. My JMP: The Distributional Costs of Net-Zero: A Heterogeneous Agent Perspective,
6. Additional Paper 1: Green Asset Pricing,
7. Additional Paper 2: Policy Interaction and the Transition to Clean Technology.

Ghassane Benmir
London School of Economics and Political Science
Houghton St, WC2A 2AE, London
and, Paris Sciences et Lettres Research University – Université Paris-Dauphine
Place Maréchal de Lattre de Tassigny, 75016 Paris, France

London, October 31, 2022

Economics Department
Columbia University
420 W 118 Street, MC 3308, New York, NY, 10027, United States

Personal Statement

Dear Economics Department of the Columbia University Committee Members,

I am Ghassane Benmir, a PhD candidate and teaching fellow at both the London School of Economics and *Paris Sciences et Lettres* Research University – Paris Dauphine. I am on the job market this year working on macro-finance and climate change and planning to submit my dissertation mid-2023. I am applying for the position of Assistant Professor as advertised on the econjobmarket.org website. I have included: i) a copy of my curriculum vitæ with references, ii) a research statement, iii) a teaching statement, iv) my teaching evaluations, v) my job market paper, titled, "The Distributional Costs of Net-Zero: A Heterogeneous Agent Perspective," and vi) two of my other papers, "Green Asset Pricing" and "Policy Interaction and the Transition To Clean Technology." In the following, I first introduce my main research. Second, I list my main academic achievements to date. Third, I present my main teaching experiences. Fourth, I outline some of my previous relevant pre-PhD experiences. Fifth, I highlight my future research and teaching plans. Finally, I conclude with my main motivations for applying to Columbia University.

My research lies at the intersection of macroeconomics, finance, and environmental economics (with an emphasis on climate economics). In my PhD research I investigate: i) how uncertainty over current climate change mitigation policies can affect macroeconomic and financial dynamics, and ii) the potential distributional impacts climate net-zero policies could have, both in the short/medium run and long run. My job market paper focuses on the distributional impacts of climate net-zero 2050 emissions policy impacts on households. It builds, on one hand, on recent advances in distributional macroeconomics, and, on the other hand, on recent climate macroeconomic modeling frameworks, developed by (two of) my advisors at the LSE (Professor Ben Moll and Professor Simon Dietz, respectively).

During my PhD, I had the opportunity to present my work at multiple high-profile conferences and workshops. Most recently, I presented my job market paper at the LSE Department of Economics Annual Environmental Week, the PSL Research Economics Seminar Series at Paris-Dauphine, the MFR Chicago Young Scholars Session, as well as at other venues. My other work (e.g. "Green Asset Pricing" and "Policy Interaction and the Transition To Clean Technology") was presented at the AEA, the EEA, the EFA, the CEBRA, the EAERE, the MIT GCFP meetings, as well as the Climate Risk Workshop of the San Francisco Fed, among others. I have also received recognition by peers for different working papers. More specifically, my co-authored paper "Green Asset Pricing" received the best paper award at the European Finance Association for Responsible Finance in 2021, while I received the runner-up prize for the QCGBF Macro-Finance Young Economist Award in 2022 for my paper, "Policy Interaction and the Transition To Clean Technology."

A major component of my PhD experience has involved teaching. I had the opportunity to hold multiple teaching positions ranging from graduate teaching assistant and course manager/teaching fellow to adjunct lecturer. I taught (and continue to teach) numerous courses at different institutions both in the U.K. and in France. At the LSE, I taught both undergraduate level courses (e.g. Microeconomics, and Macroeconomics) and post-graduate level courses (e.g. Maths for Microeconomics and Macroeconomics). As a teaching fellow/course manager for the two largest courses at the LSE, I coordinated over 15 graduate teaching assistants each term, in addition to teaching a large number of classes. I was awarded multiple prizes for high-quality teaching by the Department of Economics and was nominated by students for "Exceptional Teaching during Exceptional Times" (i.e. the pandemic). Similarly, at PSL Research – Paris Dauphine, for several years I taught macroeconomics at the undergraduate level and lectured advanced econometrics (time series) at the masters level. I also received excellent student reviews. In addition, I taught Financial Economics at the University College London (UCL), where I had excellent reviews as well, and also taught Macroeconomics for the Executive Education Program at the Imperial Business School.

Prior to embarking on the PhD, I worked for several years in consultancy on diverse projects, mainly for: i) the public sector and inter-governmental institutions, and ii) international leaders within the private sector. During these years, I built strong managerial skills, technical and soft skills, and engaged with different stakeholders, all of which have helped me during my PhD, in terms of engaging with diverse bodies of students, faculty, and academic staff in a dynamic and fruitful manner.

Moving forward, I intend to pursue research in the following directions. I intend to continue exploring uncertainty within climate dynamics and policy and the implications for policy makers, especially in the context of distributional macro-finance (i.e. accounting for heterogeneity in households, firms, and/or banks, and relying on heterogeneous agents new Keynesian (HANK) models). I also plan to dive further into the estimation of this class of models using non-linear estimation techniques to be able to construct counterfactual policy scenarios to better shape the policy decisions. On these subjects, I can envision several collaborations with researchers and academics from your institution, such as with Prof. G. Gowrisankaran, Prof. J. Sachs, Dr. M. Gomez, as well as a number of other esteemed faculty. Regarding teaching responsibilities, I would be thrilled to teach classes in macroeconomics, finance, and environmental/climate financial economics. I would also be happy to teach computational classes related to econometric techniques or financial econometrics, as well as propose (if appropriate) additional courses at the intersection of macroeconomics, finance, and climate/environmental economics. In short, I am prepared to teach courses in relation to the needs that arise.

My motivation and interest in applying for the Assistant Professor at Columbia University are multi-fold. First, joining the Economics Department at Columbia University would allow me to be part of an exciting and competitive research department, with an amazing teaching reputation, where my enthusiasm for producing cutting-edge research and delivering top-quality teaching would flourish. The dynamics of the Economics Department as well as the research conducted by the esteemed faculty at the school fits very well with my work. In particular, I believe that my research agenda fits well with the ongoing research projects at the Economics Department of the Columbia University (e.g. research conducted by Prof. G. Gowrisankaran, Prof. J. Sachs, Dr. M. Gomez, among many others). Furthermore, I believe that my teaching experience could add to the offer of courses you provide. Finally, I also have a particular interest in joining Columbia University as I would value taking up residence in the East of the United States, which would be convenient for family reasons as well.

I am available for interviews during the AEA, AFA, EEA, and EFA JM-meetings, and at other bespoke times.

Thank you for your time and consideration.

Sincerely,

Ghassane Benmir

Research Statement

Ghassane Benmir
LSE and PSL Research, October 22, 2022

My research assesses how climate change damages and climate change policies impact macroeconomic and financial aggregates, in both the short/medium run and long run. I focus on how climate change dynamics and policies impact households and firms alike. My research contributes to two main literatures: i) macro-finance and ii) environmental and climate economics. My research makes use of theoretical and numerical modeling as well as empirical approaches.

In particular, **my work seeks to advance two core research agendas**. The first addresses one of the most pressing questions in economics and finance: "What are the impacts of uncertainty over climate change dynamics and policy on the macro economy, in both the short/medium run and the long run?" The second aim is to understand how: i) the interaction between climate dynamics and policy, on one hand, and ii) the large disparities in income and wealth observed in the micro data, on the other hand, could impact the green transition, financial stability, the macro economy.

The First Research Agenda: Climate Change Uncertainty and Macro-Finance

One of the main points of disagreement in climate economics is the level of the so-called social cost of carbon (i.e. the optimal carbon price) and the short/medium-run climate policy costs. While most of the early literature on climate macro-finance ignored the role of uncertainty (relying on deterministic models to compute the social cost of carbon), recent findings show that uncertainty over climate dynamics plays a major role in shaping the social cost of carbon and induces important business cycle welfare costs. There is a need to better understand the implications of uncertainty within climate change (e.g. temperature dynamics, climate damages, and climate policy) on the social cost of carbon, as well as to better appreciate the impacts of carbon pricing on the macro economy. My work outlines three strategies to understand the implications of climate change on the macro economy.

First, I examine how uncertainty over climate dynamics and policy impacts the macro economy and financial stability. In "Policy Interaction and the Transition to Clean Technology" ([1]), we examine the aggregate impact of a market for carbon permits designed to meet climate goals (i.e. the Paris Agreement or the net-zero target) in the European Union and the role of uncertainty within climate dynamics and policy. To this end, we develop a highly tractable stochastic general equilibrium model with financial frictions, where households and producers face climate damages and policy uncertainty. We show that the feasibility of net-zero heavily depends on the level of uncertainty. We also show that financial policy is key in smoothing the impacts on financial stability as well as in smoothing the welfare aggregate costs. I further develop this line of research in [2].

Second, although most research has focused on long-run transition impacts, a recent strand of literature seeks to highlight the implications of climate policy on the business cycle. In "Green Asset Pricing" ([3]), we focus on the implications of climate policies on the business cycle and aggregate welfare. We show how climate mitigation policies have important cyclical implications, especially in terms of pre-cautionary savings, premium levels, and business cycle welfare costs, further reinforcing the importance of non-linearities and uncertainty. We also rely on non-linear estimation techniques (usually missing in the climate macro-finance literature), which allow us to run different policy counter-factual exercises using the estimated series of stochastic shocks. In "Macro-Finance, Uncertainty, and Climate Change" ([4]), I document an analogous finding demonstrating the importance of modeling choices (e.g. non-separable dis-utility of climate damages versus production climate damages) and their implications on the macro-financial aggregates.

Third, carbon prices are likely shaped by the diffusion and adoption of green innovation. "Endogenous Abatement Technology" ([5]) provides a framework, in which green innovators are financed by banks, and where loans to green innovators allow for carbon prices to decrease over time, thereby capturing the intuition that green innovation adoption is key in facilitating the transition to net-zero emissions.

The Second Research Agenda: Climate Change and Distributional Macro-Finance

In the past two decades, one of the most remarkable macroeconomic developments was the incorporation of explicit heterogeneity (e.g. in households, producers, and banks) into tractable macroeconomic frameworks. My current research (job market paper) and future work seek to contribute to this fast-growing literature, by focusing in particular on the linkages and implications of climate dynamics and policy uncertainty within distributional macro-finance.

One of the most important policy questions arising from the ambitious net-zero 2050 target is: What are the distributional costs? My job market paper—"The Distributional Costs of Net-Zero: A HANK Perspective" (jointly with J. Roman, a Ph.D. candidate at PSL Research)—focuses on the household distributional impacts of the 2050 net-zero emissions target policy in the United States, which is designed to meet climate goals (*i.e.* the pledged net-zero 2050 target). Using a Heterogeneous Agent model with full climate dynamics and household heterogeneity embedded in a two-sector production economy (energy and non-energy sectors), we show that net-zero policy increases consumption and wealth in the long run but induces distributional macroeconomic disparities in the short/medium run (e.g. by 2035, a 6-10% increase in households facing the borrowing constraint). We then show how distributing revenue from the carbon policy could partially offset consumption losses and smooth the net-zero transition. We also extend our analysis to the case of sticky prices and show how net-zero emissions induces inflationary pressure over the long run, which could represent a challenge for monetary policy conduction in a world with high inflation. Overall, the paper shows that, while climate net-zero policy is welfare enhancing, it is costly over the transition.

My next goal is to understand the implications of uncertainty on these distributional costs. A natural approach would be to extend the analysis by incorporating aggregate uncertainty, inline with the recent advances made in solving heterogeneous models with aggregate uncertainty in continuous time, relying on the master equation. I intend to work on exploring the implications of aggregate uncertainty in both climate dynamics and policy within the heterogeneous agents framework and seek to understand the implications of the green transition on households, firms, and banks.

The common denominator of my research is to develop tractable models and methods for thinking about the implications of the major challenges policy makers are facing today when designing policy. In my dissertation, I focus on climate change policy and the net-zero transition, with a specific focus on uncertainty, financial stability, and macroeconomic heterogeneity. The constant innovation in the macro-finance literature provides frameworks to address these issues, and, with my research agenda, I hope to contribute to it.

References

1. Policy interaction and the Transition to Clean Technology, Grantham Research Institute on Climate Change and the Environment, 2020, with Josselin Roman
2. ‘r star’ under the presence of the climate externality, 2022
3. Green Asset Pricing, ECB Working Paper Series, 2020, with Ivan Jaccard, and Gauthier Vermandel
4. Macro-Finance, Uncertainty, and Climate Change, 2021
5. Endogenous Abatement Technology, 2022, with Josselin Roman
6. The Distributional Costs of Net-Zero: A HANK Perspective, 2022, with Josselin Roman

Teaching Statement

Ghassane Benmir
LSE and PSL Research, October 22, 2022

As highlighted in my personal statement, a major component of my PhD experience has involved extensive teaching, academic mentoring, and course management. I enjoy teaching and lecturing deeply, and it would be a great privilege to continue to teach economics, finance, and public policy courses offered (or in need of design) at Economics and Finance Departments, Business Schools, Public Policy Schools, as well as other related departments. In the following, I first highlight the main roles I have held and the courses I have taught at the LSE and at PSL Research – Paris Dauphine. Then I detail my experiences at PSL Research – Paris Dauphine and the LSE as a graduate teaching assistant. Thereafter, I speak about my role as course manager and teaching fellow. Additionally, I touch on other courses I have taught at other schools in the U.K., before summarizing my mentoring experience. Finally, I provide a vision of my course design.

I had the opportunity to hold multiple teaching positions ranging from graduate teaching assistant and course manager/teaching fellow to adjunct lecturer. I taught (and continue to teach) numerous courses at different institutions in both the U.K. and in France. In particular, at the LSE, I taught both undergraduate level courses (e.g. EC102–Economics B, EC1A3–Microeconomics, EC1A5–Macroeconomics, and EC1B5–Macroeconomics) and post-graduate courses (e.g. EC400–Maths for Microeconomics and Macroeconomics) at the Department of Economics. Additionally, at PSL Research – Université Paris Dauphine I taught both undergraduate level courses (Macroeconomics and Introduction to Economics) and a graduate masters course (Advanced Econometrics) in the Departments of Mathematics and Economics.

I vividly remember the first class I taught at PSL Research – Université Paris Dauphine in February 2018. From that moment, I was convinced that teaching and exchanging ideas with students was one of the most fulfilling activities. I first taught Macroeconomics to first-year students at the Department of Mathematics at PSL Research – Université Paris Dauphine, where I was a graduate teaching assistant. The course evolved principally around the Solow model with a mathematical flavor, as the course was designed for mathematics students. The main challenge lied in the fact that students didn't have (in most cases) any economics background, which made the course rather a right of passage than an engagement they were initially seeking. A crucial step in the teaching process is to get the attention of students, not only because they have to follow the course and achieve good grades, but because they are genuinely interested in the content. Much like in a conference setting, students need to quickly grasp the direction of the course and the useful knowledge they can attain from it. I had to think about ways in which I could make my classes exiting and show students how complex topics in pure mathematics could have relevant policy applications in fields such as economics and finance (as I, myself, pursued an undergraduate in mathematics and physics). I found that providing a clear road map and linking the theory to concrete examples was an effective tool when teaching. Over the three years I taught Macroeconomics at PSL Research – Université Paris Dauphine, I adapted my presentations, examples, and teaching style to the needs of the students. At PSL Research – Université Paris

Dauphine students come from all walks of life and especially from different social and cultural backgrounds. Their needs are diverse and thus the way in which the class is taught is paramount for the inclusion of all. For example, I held different office hours sessions in order to accommodate the needs of different students (although in the French undergraduate system, this is unique). (In my diversity statement, I provide additional examples of inclusionary strategies that I have employed.)

At the LSE, I began my teaching duties as a graduate teaching assistant in September 2019, and since have been heavily involved with teaching within the Department of Economics. Similar to PSL Research – Université Paris Dauphine, I delivered tailor-made classes (referred to as seminars at the LSE) building within the established curriculum. For instance, first-year students often find the game theory lectures and concepts slightly difficult to comprehend. To help simplify the concepts, I set up a game during the class where students are designated as player one while I am player two. The game consists of first identifying the different possible strategies (i.e. either I speak and they listen, or they speak and I listen) and then identifying the game equilibrium. I found that involving students in such a way to be quite successful. Similarly, while teaching graduate master courses at the LSE (e.g. Maths for Microeconomics and Macroeconomics), I noted that students tend to struggle with abstract concepts related to dynamic programming (in macroeconomics). In this case, I used a concrete example of an in-house-built neoclassical growth model in Matlab to show them how the theoretical approaches map to numerical applications, using both perturbation and projection methods. While *learning by doing* contributes to a major part of the teaching experience throughout one's teaching trajectory, learning from other colleagues' experiences is key. I always seek to discuss with colleagues innovative ways to teach, which could involve: examples to use in classes, quiz strategies, types of games, and the use of digital tools. At the LSE we run official termly teaching evaluation surveys, where students evaluate their class teachers as well as their professors. While imperfect, this is often a good way to measure the involvement of the teaching staff and the efforts made in delivering quality teaching. Since my start at the LSE, I have had excellent teaching evaluations for all classes I have taught, where I was always situated in the top 5% (teaching evaluation between 4.5/5 – 4.9/5). My performance was rewarded by several prizes, including the Excellence in Teaching Award and the Highly Commended Teaching Award, both delivered by the Department of Economics. I was also twice nominated by students for Exceptional Teaching During Exceptional Times (pandemic period) and Excellence in Feedback and Support, both of which are great sources of satisfaction.

Given my dedication and experience, I was offered a teaching fellow/course manager position where I managed the two largest first-year macroeconomic courses at the LSE Department of Economics, working closely with Dr. Antonio Mele and Dr. Rachel Ngai. As a teaching fellow/course manager for these courses, I coordinated over 15 graduate teaching assistants each term, in addition to teaching a large number of classes. I was also awarded a prize for high-quality teaching and course management by the Department of Economics, especially as I was managing both courses at the same time. Similarly, at PSL Research – Université Paris Dauphine, I was offered to lecture Advanced Econometrics (time series) at the masters level given my experience and excellent teaching feedback. I have lectured time series for the previous years and have also received excellent student reviews for my lecturing. As a teaching fellow, course manager, and adjunct lecturer, the challenge arises with the level of responsibilities, but so does the intellectual reward. I learned immensely with Dr. Antonio Mele during these past three years as a course manager. We faced a number of issues ranging from student well-being to potential misconduct. Liaising with academic colleagues, faculty and administrative staff is key to manage such challenges. Clear and timely communication on one hand, and pro-active engagement on the other hand, were the two major factors that allowed for successful management of the course and its attendant situations.

In addition to my teaching at the LSE and PSL Research, I taught Financial Economics at the University College London–UCL (where I had excellent reviews as well) and taught Macroeconomics for the Executive Education Program at the Imperial Business School. Teaching at the Executive Education Program at the Imperial Business School was without a doubt one of the most interesting experiences. Executives' need are more tailored to the nature of their work. My experience in consultancy, where I managed engagements at the international level during my time at EY Advisory, came in handy in this context. The class delivery had to focus on practical aspects of macroeconomics and how they could impact the business environment, rather than focus on theory. I tailored the classes to simplify complex macroeconomic concepts, in order to link them to the real business world (e.g. how monetary policy rate setting links to inflation targeting and investments/savings choices, and how both could have an impact on firms' day-to-day business engagements).

A part of the academic journey that I find particularly rewarding is the possibility to follow students over the years and guide them in their choices. In particular, this year, I am mentoring six undergraduate students who just started their BSc in Economics at the LSE. The purpose of an academic mentor is to serve as a student's primary port of call for guidance in making academic decisions and for wider support through the student experience. Part of my responsibilities are also to provide guidance and some scope for research and creativity to my mentees in their first-year coursework competition, where the aim is to produce a 5-minute video on a selected economic theme. To create a sense of community, I meet my mentees regularly each term over coffee or lunch to discuss their progress, challenges they are facing, and we then put strategies in place to help them overcome any obstacles and to maximize their enjoyment during their time at the LSE.

Finally, regarding course design, if the opportunity allows, I would be happy to design an undergraduate and/or graduate course. I would first tailor it for the audience I will be teaching. For example, an economics department graduate course would feature higher levels of theoretical foundations than a course designed for public policy, where the approach would be more applied. Similarly, a course designed for business school MBA students would potentially feature greater elements of project-oriented work. In particular, a graduate level course for instance would require students to engage extensively with scientific papers as well as undertake projects (either replicating empirical or numerical results, or participating in group work). This would then involve students writing and delivering presentations, which will serve as preparation for future conferences, presenting in front of governments and international organizations, and engaging with different business stakeholders. The ultimate aim is to provide students with the necessary tools to achieve their goals and to be sensitive to the best means by which these tools can be delivered.

Teaching Evaluations

Ghassane Benmir

LSE and PSL Research, October 21, 2022

The following documents include all my teaching evaluations at the LSE over the past three years (i.e. 2019 to 2022). At PSL Research – Université Paris Dauphine, we do not run official evaluation surveys. I, however, have received excellent feedback from professors (e.g. Dr. Yannick Le Pen and Professor Richard Dutu) I worked with and students I taught (using unofficial teaching evaluation forms).[1] In particular, the documents are organized as follows:

- For 2019-2020 and 2020-2021 academic years, LSE education support services provided class profiles for each course taught. This summarizes the feedback from all classes taught and compares graduate teaching assistants and teaching fellows across all the department.
- For 2021-2022 academic year, LSE education support services didn't provide a class profile. I therefore included all my class evaluation surveys.
- MT 2019 document outlines the evaluations I received for teaching Economics B - Part 1 in Michaelmas Term (i.e. Autumn-Winter Term)
- LT 2020 document outlines the evaluations I received for teaching Economics B - Part 1 in Lent Term (i.e. Spring and Summer Terms)
- MT 2020 document outlines the evaluations I received for teaching Microeconomics in Michaelmas Term (i.e. Autumn-Winter Term)
- LT 2021 document outlines the evaluations I received for teaching Macroeconomics in Lent Term (i.e. Spring and Summer Terms)
- The remaining documents are all individual class surveys for MT (Microeconomics) and LT (Macroeconomics) taught in 2021-2022

[1] If needed, both Dr. Yannick Le Pen and Professor Richard Dutu, would be happy to provide detailed feedback.

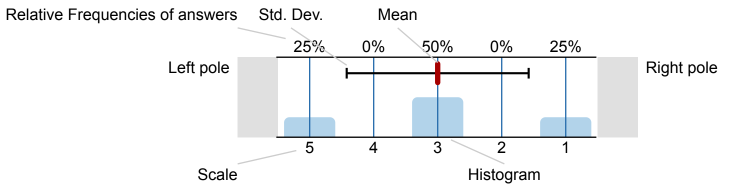
Ghassane Benmir
Instructor profile
No. of responses = 56

Overall indicators

		5	4	3	2	1		
# Global Index	+						-	av.=4.3 dev.=0.8
Class/Seminar Teacher Evaluation (Scale width: 5)	+						-	av.=4.5 dev.=0.6
Course Evaluation (Scale width: 5)	+						-	av.=4.1 dev.=0.9

Legend

Question text



n=No. of responses
av.=Mean
dev.=Std. Dev.
ab.=Abstention
cf=Cumulative Frequency

Class/Seminar Teacher Evaluation

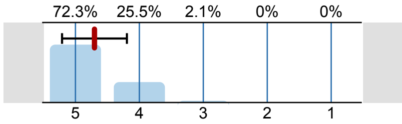
		5	4	3	2	1		
1.1 The teacher communicated ideas and concepts effectively.	Definitely Agree	60.7%	37.5%	1.8%	0%	0%	Definitely Disagree	n=56 av.=4.6 dev.=0.5 cf=98.21%
1.2 The teacher has improved my understanding of the course content.	Definitely Agree	58.9%	39.3%	0%	1.8%	0%	Definitely Disagree	n=56 av.=4.6 dev.=0.6 cf=98.21%
1.3 The teacher has made the subject interesting.	Definitely Agree	42.9%	35.7%	16.1%	5.4%	0%	Definitely Disagree	n=56 av.=4.2 dev.=0.9 cf=78.57%
1.4 The teacher is good at involving members of the class/seminar.	Definitely Agree	50%	37.5%	12.5%	0%	0%	Definitely Disagree	n=56 av.=4.4 dev.=0.7 cf=87.50%

1.5 Have you received feedback on your work from this teacher?

Yes	94.6%	n=56
No	5.4%	

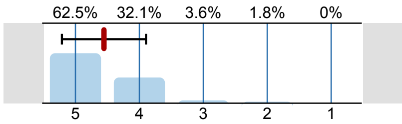
		5	4	3	2	1		
1.5b Feedback on my work has been timely (typically 3-4 weeks after submission).	Definitely Agree	90.6%	9.4%	0%	0%	0%	Definitely Disagree	n=53 av.=4.9 dev.=0.3 cf=100.00%
1.5c I have received helpful comments on my work.	Definitely Agree	58.5%	37.7%	1.9%	0%	1.9%	Definitely Disagree	n=53 av.=4.5 dev.=0.7 cf=96.23%

1.5d I was able to seek further clarification on feedback from the teacher where needed.

Definitely Agree  Definitely Disagree

n=47
av.=4.7
dev.=0.5
ab.=6
cf=97.87%

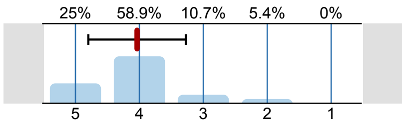
1.6 Overall, I am satisfied with the class/seminar teaching by this teacher on this course.

Definitely Agree  Definitely Disagree

n=56
av.=4.6
dev.=0.7
cf=94.64%

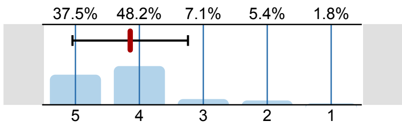
Course Evaluation

2.1 This course has challenged me to achieve my best work.

Definitely Agree  Definitely Disagree

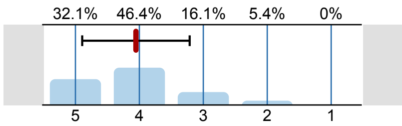
n=56
av.=4
dev.=0.8
cf=83.93%

2.2 This course is intellectually stimulating.

Definitely Agree  Definitely Disagree

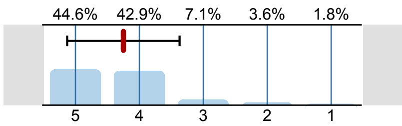
n=56
av.=4.1
dev.=0.9
cf=85.71%

2.3 I have received sufficient advice and guidance in relation to this course to date.

Definitely Agree  Definitely Disagree

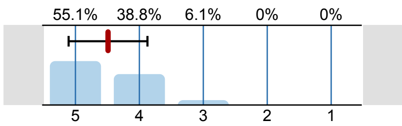
n=56
av.=4.1
dev.=0.8
cf=78.57%

2.4 I am satisfied with the amount of contact time with teachers for this course.

Definitely Agree  Definitely Disagree

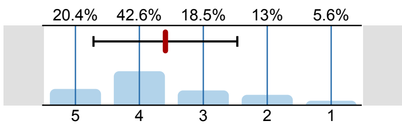
n=56
av.=4.3
dev.=0.9
cf=87.50%

2.5 I have been able to contact staff about this course when I needed to.

Definitely Agree  Definitely Disagree

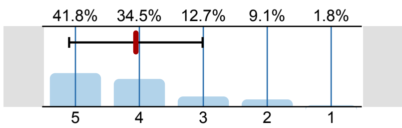
n=49
av.=4.5
dev.=0.6
ab.=7
cf=93.88%

2.6 The criteria used in marking have been clear in advance.

Definitely Agree  Definitely Disagree

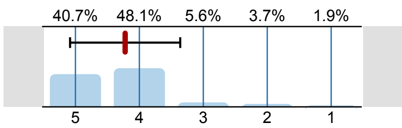
n=54
av.=3.6
dev.=1.1
ab.=2
cf=62.96%

2.7 Marking and assessment has been fair.

Definitely Agree  Definitely Disagree

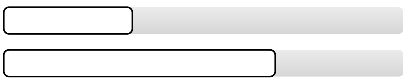
n=55
av.=4.1
dev.=1
ab.=1
cf=76.36%

2.8 The feedback I received has helped my learning and performance on the course.

Definitely Agree  Definitely Disagree

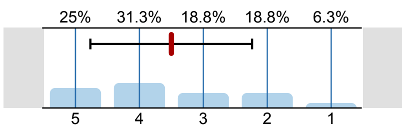
n=54
av.=4.2
dev.=0.9
ab.=2
cf=88.89%

2.9 Do you have a reading list for this course?

Yes
No

32.1%
67.9%

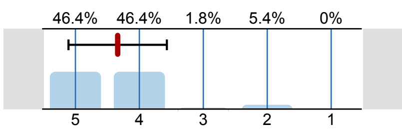
n=56

2.9b The reading list(s) was useful for my learning.

Definitely Agree  Definitely Disagree

n=16
av.=3.5
dev.=1.3
ab.=2
cf=56.25%

2.10 I found Moodle useful for my studies on this course.

Definitely Agree  Definitely Disagree

n=56
av.=4.3
dev.=0.8
cf=92.86%

2.11 The course material provided was useful for my studies and learning.

Definitely Agree	5	4	3	2	1	Definitely Disagree	
	35.7%	39.3%	14.3%	8.9%	1.8%		n=56 av.=4 dev.=1 cf=75.00%

2.12 Do you have lectures for this course?

Yes	96.4%	n=56
No	3.6%	

2.12b I am satisfied with the integration of classes/ seminars with lectures on this course.

Definitely Agree	5	4	3	2	1	Definitely Disagree	
	41.5%	45.3%	3.8%	7.5%	1.9%		n=53 av.=4.2 dev.=1 cf=86.79%

2.13 Overall, I am satisfied with my experience on this course.

Definitely Agree	5	4	3	2	1	Definitely Disagree	
	28.6%	46.4%	19.6%	3.6%	1.8%		n=56 av.=4 dev.=0.9 cf=75.00%

2.14 Would you recommend this course to other students?

Yes	57.1%	n=56
Maybe	35.7%	
No	7.1%	

Your Information

3.1 Which of the reasons given below describe why you are taking the course? *(Please select all that apply)*

It is compulsory for my degree programme	89.3%	n=56
I chose the course as an option for my degree programme	10.7%	
I am interested in the subject matter	17.9%	
It was recommended to me by other students	1.8%	
It was recommended to me by an academic	0%	
Other	0%	

3.1b Was this your 1st, 2nd, 3rd or other choice?

1st choice	83.3%	n=6
2nd choice	16.7%	
3rd choice	0%	
Other choice	0%	

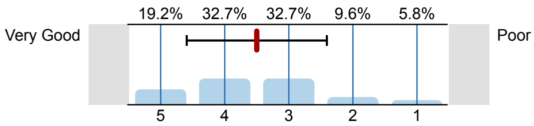
3.1c In relation to what you wanted to study, how important was choosing this course to you?

Very Important	5	4	3	2	1	Not at all Important	
	16.7%	50%	0%	16.7%	16.7%		n=6 av.=3.3 dev.=1.5

3.2 How many hours of independent study do you put into this course each week outside of lectures, classes, and seminars?

More than 10 hours	1.8%	n=55
6-10 hours	14.5%	
2-5 hours	61.8%	
Less than 2 hours	18.2%	
None	3.6%	
N/A	0%	

3.3 Please rate your own contribution to classes/ seminars.



n=52
av.=3.5
dev.=1.1
ab.=2

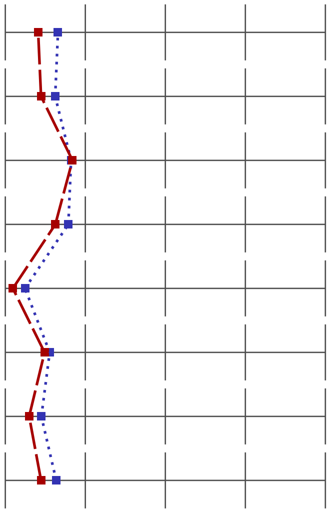
Profile

Compilation: Instructor profile

Comparative line: MT19 class Survey Economics

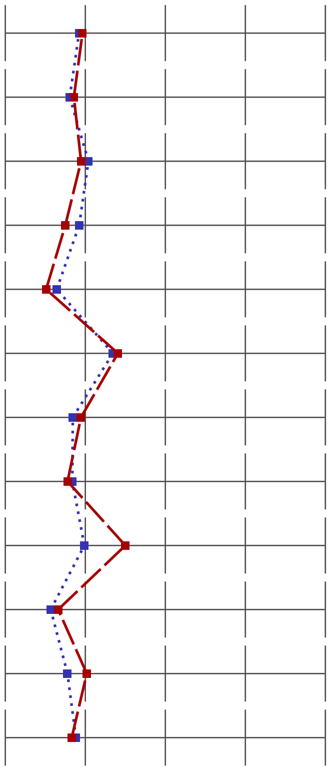
Values used in the profile line: Mean

Class/Seminar Teacher Evaluation

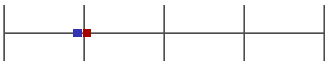


1.1 The teacher communicated ideas and concepts effectively.	Definitely Agree	Definitely Disagree	n=56 n=2586	av.=4.6 av.=4.3
1.2 The teacher has improved my understanding of the course content.	Definitely Agree	Definitely Disagree	n=56 n=2585	av.=4.6 av.=4.4
1.3 The teacher has made the subject interesting.	Definitely Agree	Definitely Disagree	n=56 n=2583	av.=4.2 av.=4.2
1.4 The teacher is good at involving members of the class/seminar.	Definitely Agree	Definitely Disagree	n=56 n=2577	av.=4.4 av.=4.2
1.5b Feedback on my work has been timely (typically 3-4 weeks after submission).	Definitely Agree	Definitely Disagree	n=53 n=2125	av.=4.9 av.=4.8
1.5c I have received helpful comments on my work.	Definitely Agree	Definitely Disagree	n=53 n=2117	av.=4.5 av.=4.4
1.5d I was able to seek further clarification on feedback from the teacher where needed.	Definitely Agree	Definitely Disagree	n=47 n=1913	av.=4.7 av.=4.5
1.6 Overall, I am satisfied with the class/seminar teaching by this teacher on this course.	Definitely Agree	Definitely Disagree	n=56 n=2587	av.=4.6 av.=4.4

Course Evaluation

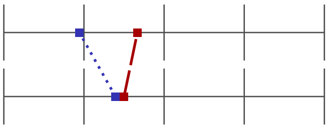


2.1 This course has challenged me to achieve my best work.	Definitely Agree	Definitely Disagree	n=56 n=2581	av.=4.0 av.=4.1
2.2 This course is intellectually stimulating.	Definitely Agree	Definitely Disagree	n=56 n=2584	av.=4.1 av.=4.2
2.3 I have received sufficient advice and guidance in relation to this course to date.	Definitely Agree	Definitely Disagree	n=56 n=2559	av.=4.1 av.=4.0
2.4 I am satisfied with the amount of contact time with teachers for this course.	Definitely Agree	Definitely Disagree	n=56 n=2551	av.=4.3 av.=4.1
2.5 I have been able to contact staff about this course when I needed to.	Definitely Agree	Definitely Disagree	n=49 n=2278	av.=4.5 av.=4.4
2.6 The criteria used in marking have been clear in advance.	Definitely Agree	Definitely Disagree	n=54 n=2463	av.=3.6 av.=3.7
2.7 Marking and assessment has been fair.	Definitely Agree	Definitely Disagree	n=55 n=2314	av.=4.1 av.=4.2
2.8 The feedback I received has helped my learning and performance on the course.	Definitely Agree	Definitely Disagree	n=54 n=2383	av.=4.2 av.=4.2
2.9b The reading list(s) was useful for my learning.	Definitely Agree	Definitely Disagree	n=16 n=1339	av.=3.5 av.=4.0
2.10 I found Moodle useful for my studies on this course.	Definitely Agree	Definitely Disagree	n=56 n=2566	av.=4.3 av.=4.4
2.11 The course material provided was useful for my studies and learning.	Definitely Agree	Definitely Disagree	n=56 n=2556	av.=4.0 av.=4.2
2.12b I am satisfied with the integration of classes/ seminars with lectures on this course.	Definitely Agree	Definitely Disagree	n=53 n=2475	av.=4.2 av.=4.1

2.13 Overall, I am satisfied with my experience on this course. | Definitely Agree  Definitely Disagree | n=56 av.=4.0 | n=2587 av.=4.1

Your Information

3.1c In relation to what you wanted to study, how important was choosing this course to you? | Very Important — Not at all Important | n=6 av.=3.3 | n=749 av.=4.1

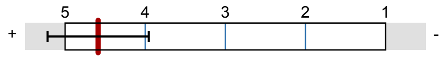


3.3 Please rate your own contribution to classes/ seminars. | Very Good — Poor | n=52 av.=3.5 | n=2481 av.=3.6

Ghassane Benmir
Instructor profile
No. of responses = 15

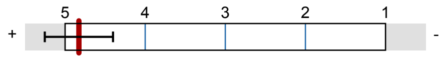
Overall indicators

Global Index



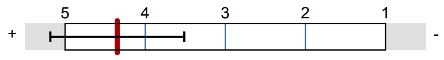
av.=4.6
dev.=0.6

Class/Seminar Teacher Evaluation (Scale width: 5)



av.=4.8
dev.=0.4

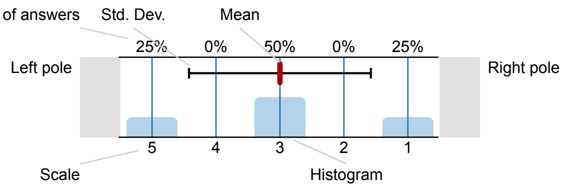
Course Evaluation (Scale width: 5)



av.=4.3
dev.=0.8

Legend

Question text



n=No. of responses
av.=Mean
dev.=Std. Dev.
ab.=Abstention
cf=Cumulative Frequency

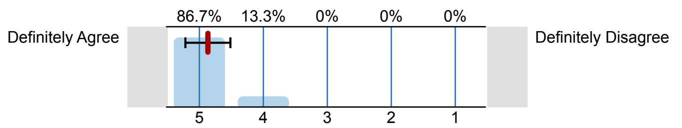
1. Class/Seminar Teacher Evaluation

This survey requests your feedback on two separate aspects of your learning experience, split into three sections. The first section asks for your views on your teacher’s class/seminar teaching. The second section asks for your views on the course as a whole *at this point in time*. Finally, the third section asks for some information about you, to aid analysis.Your views are valuable to your teacher and to the School. The results will be used to identify good practice and will also be used to help improve the teaching and learning experience for you and your peers.

The School reports internal survey results as the percentage of respondents who 'mostly agree' or 'definitely agree' with each statement, in comparison to the percentage of respondents who either 'mostly disagree' or 'definitely disagree' or 'neither agree nor disagree'. The percentage of respondents who 'mostly agree' or 'definitely agree' is the ‘% Agree’ result. For example, the % Agree score means that X % of students on Y course mostly or definitely agree with the statement 'I have received helpful comments on my work'.

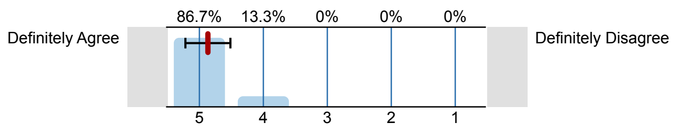
Please show the extent of your agreement by selecting the box that reflects your current view of your class/seminar teacher:

1.1) 1.1 The teacher communicated ideas and concepts effectively.



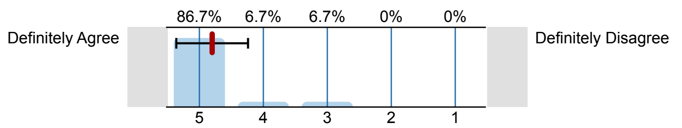
n=15
av.=4.9
dev.=0.4
cf=100.00%

1.2) 1.2 The teacher has improved my understanding of the course content.



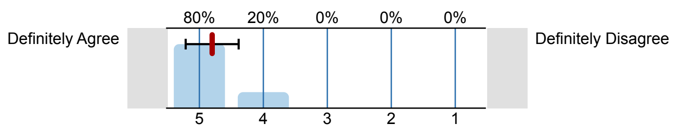
n=15
av.=4.9
dev.=0.4
cf=100.00%

1.3) 1.3 The teacher has made the subject interesting.



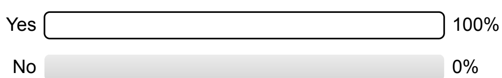
n=15
av.=4.8
dev.=0.6
cf=93.33%

1.4) 1.4 The teacher is good at involving members of the class/seminar.



n=15
av.=4.8
dev.=0.4
cf=100.00%

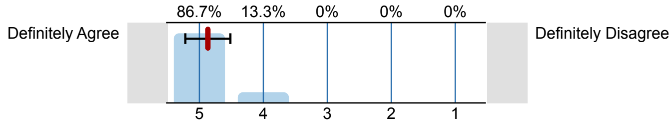
1.5) 1.5 Have you received feedback on your work from this teacher?



n=15

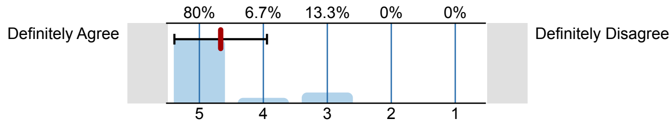
Please show the extent of your agreement by selecting the box that reflects your current view of your class/seminar teacher:

1.6) 1.5b Feedback on my work has been timely (typically 3-4 weeks after submission).



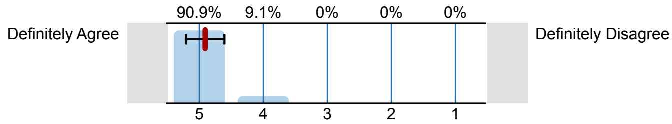
n=15
av.=4.9
dev.=0.4
cf=100.00%

1.7) 1.5c I have received helpful comments on my work.



n=15
av.=4.7
dev.=0.7
cf=86.67%

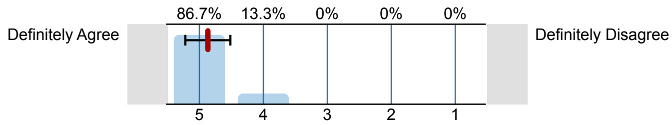
1.8) 1.5d I was able to seek further clarification on feedback from the teacher where needed.



n=11
av.=4.9
dev.=0.3
ab.=3
cf=100.00%

Please show the extent of your agreement by selecting the box that reflects your current view of your class/seminar teacher:

1.9) 1.6 Overall, I am satisfied with the class/seminar teaching by this teacher on this course.



n=15
av.=4.9
dev.=0.4
cf=100.00%

1.10) 1.7 Please comment below on aspects of this teacher's class/seminar teaching you think were particularly helpful.

- Connection of lecture material to macro environment nowadays
- Ghassane is an outstanding class teacher. He goes through each topic carefully, always asks if there is anything we don't understand and is always willing to give extra help to us if we require it.
  I am very happy with Ghassane's teaching and strongly attribute my grade (only January exam so far) to his teaching.
- It was really useful how Ghassane went through the questions as we should write them in the exam, ie by clearly linking to course topics.
- Teacher is easily approachable and very friendly.
  Good at involving the class.
  Good emphasis on using proper terminologies.
- Time allocated to each question
  Explanations
  Bord Writting

1.11) 1.7b Please comment below on aspects of this teacher's class/seminar teaching you think could be improved.

- -
- Explanations aren't always clear/sometimes can be hard to follow.
  Sometimes the class can feel boring, though this is not true most of the time.
- The best lse teacher I met so far!

2. Thank you - Part 1 Complete

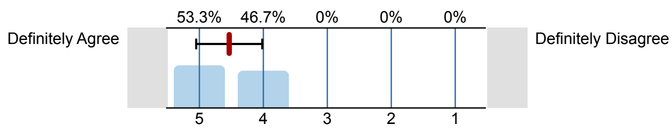
Thank you for completing the teacher evaluation of the class/seminar survey.

The next part of the survey asks for your views on the course as a whole. It is not restricted to this particular teacher, but to the entire experience you have had on this course to date.

3. Course Evaluation

Please show the extent of your agreement by selecting the box that reflects your current view of your experience on this course to date:

3.1) 2.1 This course has challenged me to achieve my best work.



n=15
av.=4.5
dev.=0.5
cf=100.00%

3.2) 2.2 This course is intellectually stimulating.

	5	4	3	2	1		
Definitely Agree	53.3%	46.7%	0%	0%	0%	Definitely Disagree	n=15 av.=4.5 dev.=0.5 cf=100.00%

3.3) 2.3 I have received sufficient advice and guidance in relation to this course to date.

	5	4	3	2	1		
Definitely Agree	46.7%	33.3%	13.3%	6.7%	0%	Definitely Disagree	n=15 av.=4.2 dev.=0.9 cf=80.00%

3.4) 2.4 I am satisfied with the amount of contact time with teachers for this course.

	5	4	3	2	1		
Definitely Agree	53.3%	40%	6.7%	0%	0%	Definitely Disagree	n=15 av.=4.5 dev.=0.6 cf=93.33%

3.6) 2.5 I have been able to contact staff about this course when I needed to.

	5	4	3	2	1		
Definitely Agree	58.3%	41.7%	0%	0%	0%	Definitely Disagree	n=12 av.=4.6 dev.=0.5 ab.=3 cf=100.00%

Please show the extent of your agreement by selecting the box that reflects your current view of your experience on this course to date:

3.7) 2.6 The criteria used in marking have been clear in advance.

	5	4	3	2	1		
Definitely Agree	53.3%	26.7%	0%	0%	20%	Definitely Disagree	n=15 av.=3.9 dev.=1.6 cf=80.00%

3.8) 2.7 Marking and assessment has been fair.

	5	4	3	2	1		
Definitely Agree	46.7%	26.7%	6.7%	0%	20%	Definitely Disagree	n=15 av.=3.8 dev.=1.6 cf=73.33%

3.9) 2.8 The feedback I received has helped my learning and performance on the course.

	5	4	3	2	1		
Definitely Agree	46.7%	46.7%	0%	6.7%	0%	Definitely Disagree	n=15 av.=4.3 dev.=0.8 cf=93.33%

3.10) 2.9 Do you have a reading list for this course?

Yes	26.7%	n=15
No	73.3%	

3.11) 2.9b The reading list(s) was useful for my learning.

	5	4	3	2	1		
Definitely Agree	25%	25%	25%	25%	0%	Definitely Disagree	n=4 av.=3.5 dev.=1.3 cf=50.00%

3.12) 2.10 I found Moodle useful for my studies on this course.

	5	4	3	2	1		
Definitely Agree	66.7%	26.7%	6.7%	0%	0%	Definitely Disagree	n=15 av.=4.6 dev.=0.6 cf=93.33%

3.13) 2.11 The course material provided was useful for my studies and learning.

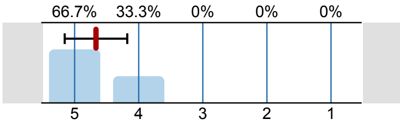
	5	4	3	2	1		
Definitely Agree	46.7%	46.7%	6.7%	0%	0%	Definitely Disagree	n=15 av.=4.4 dev.=0.6 cf=93.33%

3.14) 2.12 Do you have lectures for this course?

Yes	100%	n=15
No	0%	

3.15) 2.12b I am satisfied with the integration of classes/ seminars with lectures on this course.

Definitely Agree

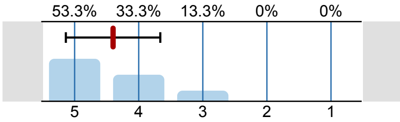


Definitely Disagree

n=15
av.=4.7
dev.=0.5
cf=100.00%

3.16) 2.13 Overall, I am satisfied with my experience on this course.

Definitely Agree



Definitely Disagree

n=15
av.=4.4
dev.=0.7
cf=86.67%

3.17) 2.14 Would you recommend this course to other students?

Yes	86.7%	n=15
Maybe	6.7%	
No	6.7%	

3.18) 2.15 Please comment below on aspects of this course you think were particularly good.

- Content
  Lecturer
- I like how this course covers all the key concepts in Macro and Francesco takes time to explain each topic in depth and gives extra time to the topics which are more difficult.
- The way the course places a focus on intuitive understanding so that we don't get lost in formulas/numbers.

3.19) 2.15b Please comment below on aspects of this course you think could be improved.

- Although this is only an introductory course, I would have liked some things to be studied more in depth.
- Just the overall examination format, which isn't quite the best way to showcase a candidate's understanding and ability. While the marking format for the MCQs is well-intentioned in trying to weed out students who are just guessing, since many times (especially in the quizzes for this Macro courses) the options are often highly ambiguous, and hence this makes the quiz tricky, in a bad way. For the long questions, I also find the marking scheme inflexible since the professor insists that we must adhere to the set of points he has outlined. Even if we may have other points that are also valid, we end up being penalized for that as it is considered "irrelevant", and I find this rather unfair.
- Lecture Notes
  Quiz content

4. Your Information

4.1) 3.1 Which of the reasons given below describe why you are taking the course? *(Please select all that apply)*

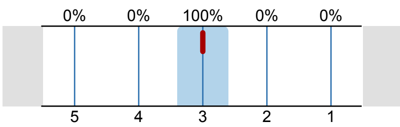
It is compulsory for my degree programme	93.3%	n=15
I chose the course as an option for my degree programme	6.7%	
I am interested in the subject matter	20%	
It was recommended to me by other students	0%	
It was recommended to me by an academic	0%	
Other	0%	

4.2) 3.1b Was this your 1st, 2nd, 3rd or other choice?

1st choice	100%	n=1
2nd choice	0%	
3rd choice	0%	
Other choice	0%	

4.3) 3.1c In relation to what you wanted to study, how important was choosing this course to you?

Very Important



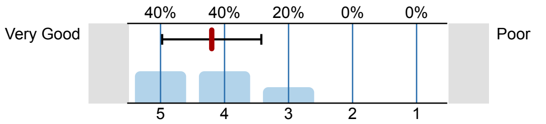
Not at all Important

n=1
av.=3
dev.=0

4.4) 3.2 How many hours of independent study do you put into this course each week outside of lectures, classes, and seminars?

More than 10 hours	13.3%	n=15
6-10 hours	20%	
2-5 hours	40%	
Less than 2 hours	26.7%	
None	0%	
N/A	0%	

4.5) 3.3 Please rate your own contribution to classes/ seminars.



n=15
av.=4.2
dev.=0.8

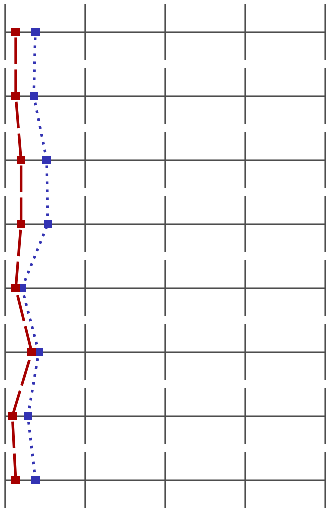
Profile

Compilation: Instructor profile

Comparative line: LT20_Economics class survey

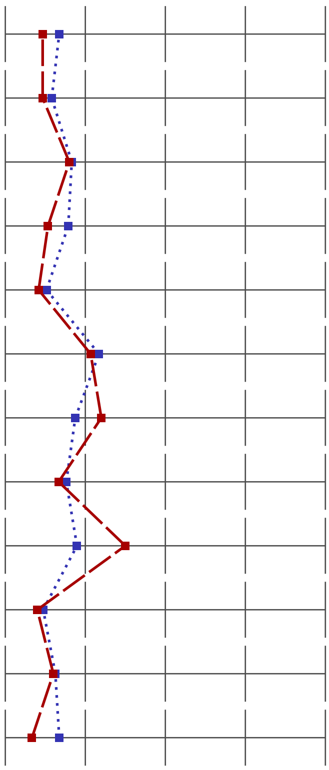
Values used in the profile line: Mean

1. Class/Seminar Teacher Evaluation



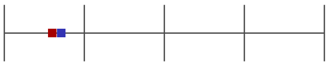
1.1)	1.1 The teacher communicated ideas and concepts effectively.	Definitely Agree	Definitely Disagree	n=15 n=1402	av.=4.9 av.=4.6
1.2)	1.2 The teacher has improved my understanding of the course content.	Definitely Agree	Definitely Disagree	n=15 n=1402	av.=4.9 av.=4.6
1.3)	1.3 The teacher has made the subject interesting.	Definitely Agree	Definitely Disagree	n=15 n=1401	av.=4.8 av.=4.5
1.4)	1.4 The teacher is good at involving members of the class/seminar.	Definitely Agree	Definitely Disagree	n=15 n=1400	av.=4.8 av.=4.5
1.6)	1.5b Feedback on my work has been timely (typically 3-4 weeks after submission).	Definitely Agree	Definitely Disagree	n=15 n=1187	av.=4.9 av.=4.8
1.7)	1.5c I have received helpful comments on my work.	Definitely Agree	Definitely Disagree	n=15 n=1184	av.=4.7 av.=4.6
1.8)	1.5d I was able to seek further clarification on feedback from the teacher where needed.	Definitely Agree	Definitely Disagree	n=11 n=1113	av.=4.9 av.=4.7
1.9)	1.6 Overall, I am satisfied with the class/seminar teaching by this teacher on this course.	Definitely Agree	Definitely Disagree	n=15 n=1403	av.=4.9 av.=4.6

3. Course Evaluation



3.1)	2.1 This course has challenged me to achieve my best work.	Definitely Agree	Definitely Disagree	n=15 n=1401	av.=4.5 av.=4.3
3.2)	2.2 This course is intellectually stimulating.	Definitely Agree	Definitely Disagree	n=15 n=1400	av.=4.5 av.=4.4
3.3)	2.3 I have received sufficient advice and guidance in relation to this course to date.	Definitely Agree	Definitely Disagree	n=15 n=1389	av.=4.2 av.=4.2
3.4)	2.4 I am satisfied with the amount of contact time with teachers for this course.	Definitely Agree	Definitely Disagree	n=15 n=1398	av.=4.5 av.=4.2
3.6)	2.5 I have been able to contact staff about this course when I needed to.	Definitely Agree	Definitely Disagree	n=12 n=1313	av.=4.6 av.=4.5
3.7)	2.6 The criteria used in marking have been clear in advance.	Definitely Agree	Definitely Disagree	n=15 n=1364	av.=3.9 av.=3.8
3.8)	2.7 Marking and assessment has been fair.	Definitely Agree	Definitely Disagree	n=15 n=1314	av.=3.8 av.=4.1
3.9)	2.8 The feedback I received has helped my learning and performance on the course.	Definitely Agree	Definitely Disagree	n=15 n=1334	av.=4.3 av.=4.2
3.11)	2.9b The reading list(s) was useful for my learning.	Definitely Agree	Definitely Disagree	n=4 n=728	av.=3.5 av.=4.1
3.12)	2.10 I found Moodle useful for my studies on this course.	Definitely Agree	Definitely Disagree	n=15 n=1393	av.=4.6 av.=4.5
3.13)	2.11 The course material provided was useful for my studies and learning.	Definitely Agree	Definitely Disagree	n=15 n=1391	av.=4.4 av.=4.4
3.15)	2.12b I am satisfied with the integration of classes/ seminars with lectures on this course.	Definitely Agree	Definitely Disagree	n=15 n=1343	av.=4.7 av.=4.3

3.16) 2.13 Overall, I am satisfied with my experience on this course. — Definitely Agree

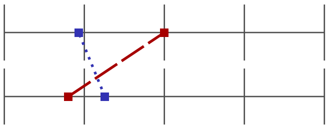


Definitely Disagree — n=15 av.=4.4 / n=1403 av.=4.3

4. Your Information

4.3) 3.1c In relation to what you wanted to study, how important was choosing this course to you? — Very Important / Not at all Important — n=1 av.=3.0 / n=495 av.=4.1

4.5) 3.3 Please rate your own contribution to classes/ seminars. — Very Good / Poor — n=15 av.=4.2 / n=1339 av.=3.7



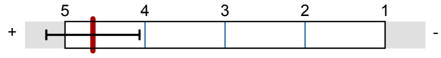
Ghassane Benmir
Instructor profile
No. of responses = 56

Overall indicators

Global Index

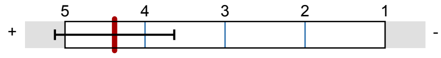
av.=4.5
dev.=0.7

Class/Seminar Teacher Evaluation (Scale width: 5)



av.=4.7
dev.=0.6

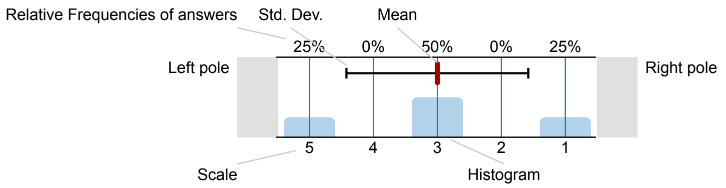
Course Evaluation (Scale width: 5)



av.=4.4
dev.=0.7

Legend

Question text



n=No. of responses
av.=Mean
dev.=Std. Dev.
ab.=Abstention
cf=Cumulative Frequency

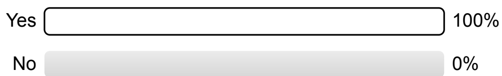
1. Class/Seminar Teacher Evaluation

This survey requests your feedback on two separate aspects of your learning experience, split into three sections. The first section asks for your views on your teacher's class/seminar teaching. The second section asks for your views on the course as a whole at this point in time. Finally, the third section asks for some information about you, to aid analysis.

We recognise that this term has been particularly challenging for everyone due to the wider public health situation, with disruption experienced by both students and teaching staff. The School is continually striving to deliver the best possible educational experience despite these challenges and your views about your learning experience at LSE are a valuable source of information about this. The results will be used to help improve the teaching and learning experience for you and your peers and to identify good practice.

The School assumes that your response is broadly positive if you 'mostly agree' or 'definitely agree' with a statement.

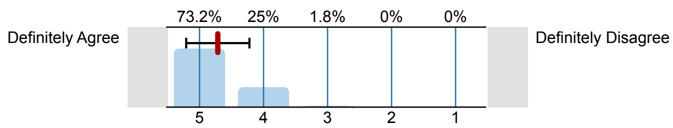
1.1) Do the answers you supply below relate to the teacher from whom you have received the majority of your class/seminar teaching this term? The teacher's name, course title and group number (where relevant) are provided in the invitation email you have received for the survey.



n=52

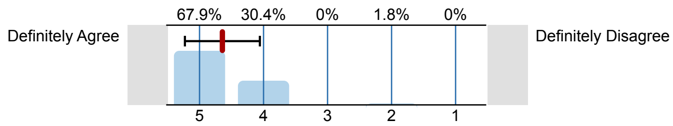
Please show the extent of your agreement by selecting the box that reflects your current view of your class/seminar teacher:

1.2) 1.1 The teacher communicated ideas and concepts effectively.



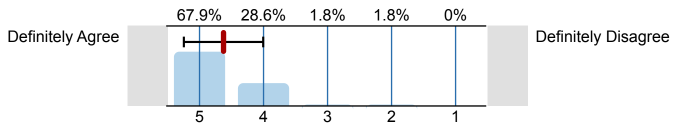
n=56
av.=4.7
dev.=0.5
cf=98.21%

1.3) 1.2 The teacher has improved my understanding of the course content.



n=56
av.=4.6
dev.=0.6
cf=98.21%

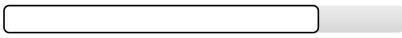
1.4) 1.3 The teacher has made the subject interesting.



n=56
av.=4.6
dev.=0.6
cf=96.43%

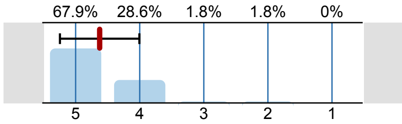
1.5) 1.4 Have you attended classes/seminars for this class/seminar:

on-campus  17.9% n=56

online  78.6%

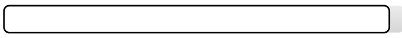
both  3.6%

1.6) 1.4b The teacher is good at involving members of the class/seminar.

Definitely Agree  Definitely Disagree

n=56
av.=4.6
dev.=0.6
cf=96.43%

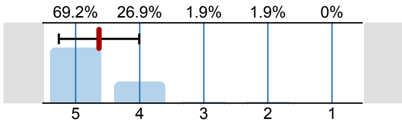
1.7) 1.5 Have you received feedback on your work from this teacher?

Yes  96.3% n=54

No  3.7%

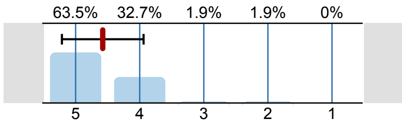
Please show the extent of your agreement by selecting the box that reflects your current view of your class/seminar teacher:

1.8) 1.5b Feedback on my work has been timely (typically 3-4 weeks after submission).

Definitely Agree  Definitely Disagree

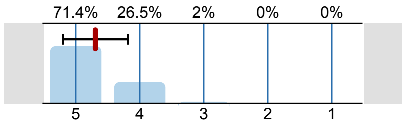
n=52
av.=4.6
dev.=0.6
cf=96.15%

1.9) 1.5c I have received helpful comments on my work.

Definitely Agree  Definitely Disagree

n=52
av.=4.6
dev.=0.6
cf=96.15%

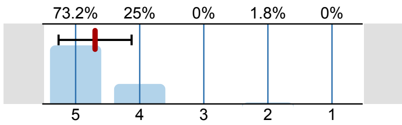
1.10) 1.5d I was able to seek further clarification on feedback from the teacher where needed.

Definitely Agree  Definitely Disagree

n=49
av.=4.7
dev.=0.5
ab.=3
cf=97.96%

Please show the extent of your agreement by selecting the box that reflects your current view of your class/seminar teacher:

1.11) 1.6 Overall, I am satisfied with the class/seminar teaching by this teacher on this course.

Definitely Agree  Definitely Disagree

n=56
av.=4.7
dev.=0.6
cf=98.21%

1.12) 1.7 Please comment below on aspects of this teacher's class/seminar teaching you think were particularly helpful.

- Clear explanation of every problem set. Remind us the things that need to be covered in the answer such as plotting a graph to help the explanation.
- Clear explanation of the problem sets
- Engaged us during the lessons through person-specific questions.
- Free chat session. Appreciated it a lot.
- Going through the week's summary before class
- Good explanations on how to answer the questions on exams.
- He always show us the summary of the course each week, which i can have a more clear understanding about this course.
- He does a lecture summary right before going into mcqs/ problem sets which I found to be extremely helpful. he also stays behind 10-15mins after the class actually ends so we can clarify any questions that we may have.
- He explains the concepts very clearly
- He gives very detailed feedback of submitted work and his classes are engaging. He tries to get students involved in the lessons.
- His enthusiasm for the subject and helping us understand the course. He tries his best to integrate the students of the class, which is great
- Kind, fast paced, very helpful topic summaries

- Mr Ghassane is willing to take time to answer our doubts, thought it often leads to lack of time to discuss the last questions in our problem set.
- Our class teacher went through every part of the problem set with great details. This was quite helpful!
- Provided audio feedback. Nice touch showing effort in overcoming the walls of virtual learning
- Teacher gives us opportunities to ask questions after the lesson, which is I believe a really useful extra 10 minutes for us.
- The explanation of the questions is really clear and easy for me to understand. This helps me have a better understanding of knowledge.
- The feedback given on problem sets really help me to better understand what types of answers are being looking for and how to structure my answers by combining explanations in words and graphs. The use of real-life examples while explaining questions in quizzes and problem sets are also helpful in understanding the situation.
- The summary of the previous week’s content at the beginning of each class and putting the problems in real word contexts are both very helpful.
- The teacher interacts with the students, which helps in improving the level of involvement and understanding.
- The teacher stays longer than usual in the classes in case we want to ask questions, and always connects out topics to global issues and shows the application of what we learn in real-world examples.
- The teacher talks through each question with specific problems which I think are very helpful.
- The teaching was done at a very good pace, not too slow not too fast. He encourages all to participate and help us with the harder questions.
- The use of simplified examples
- Thorough explanation of each topics. Interaction between students by purposefully making explanations wrong.
- Very positive and lively
- Writes down common mistakes that people make in class to see if we can spot the mistake, then corrects it after if no one spots the problem with the working out or the answer.
- after class sessions where we discussed about concepts and ask questions were really helpful
- very clear teaching during classes and provided audio feedback which i really appreciated

---

1.13) 1.7b Please comment below on aspects of this teacher's class/seminar teaching you think could be improved.

- -
- 1. Please Spend more time on the problem set instead of the quiz.

  2. Please try to mark and provide more individual feedback problem set.
- A bit more of time keeping is appreciated.
- Everything is fine now!! The time management of classes greatly improve during the semester!
- I don't know if it is my teacher's fault, but my class lack discussion. Although I've seen my teacher trying to encourage my class to be more active, I feel only a few of us talk.
- It would be very nice if we can have a recording of the class
- Maybe give some exam tips.
- My teacher gave me very detailed feedback via audio on my problem set 7 which I really appreciate but I think it'd be a better idea if him could give us written feedback because the audio was a bit difficult for me to hear. Plus written feedback is more clear and quicker to access.
- Nothing
- Nothing that I can think of on the top of my head.
- Nothing.
- Slightly more focus on exams - what type of questions, and where marks are allocated
- Sometimes the class time extend beyonds an hour.
- Sometimes, the ideas could be explained a bit more clearly

- nothing really, i thoroughly enjoy classes and find them to be very helpful in clarifying content
- providing feedback on our submitted work more often if possible
- the quality of sound in classes is not that good, there are some noise when speaking.

2. Thank you - Part 1 Complete

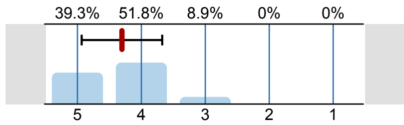
Thank you for completing the teacher evaluation of the class/seminar survey.

The next part of the survey asks for your views on the course as a whole. It is not restricted to this particular teacher, but to the entire experience you have had on this course to date.

3. Course Evaluation

Please show the extent of your agreement by selecting the box that reflects your current view of your experience on this course to date:

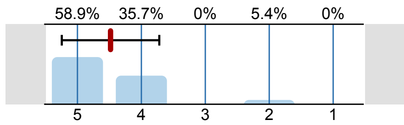
3.1) 2.1 This course has challenged me to achieve my best work.

Definitely Agree


Definitely Disagree

n=56
av.=4.3
dev.=0.6
cf=91.07%

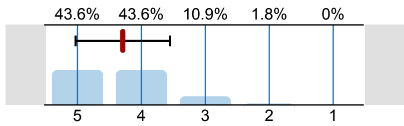
3.2) 2.2 This course is intellectually stimulating.

Definitely Agree


Definitely Disagree

n=56
av.=4.5
dev.=0.8
cf=94.64%

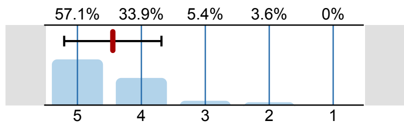
3.3) 2.3 I have received sufficient advice and guidance in relation to this course to date.

Definitely Agree


Definitely Disagree

n=55
av.=4.3
dev.=0.7
ab.=1
cf=87.27%

3.4) 2.4 I am satisfied with the amount of contact time with teachers for this course.

Definitely Agree


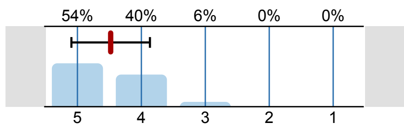
Definitely Disagree

n=56
av.=4.4
dev.=0.8
cf=91.07%

3.5) 2.4b Please comment below about why contact time with teachers has been less than satisfactory.

- I think we should have more classes because there is not enough time within an hour in a week to talk about everything about the topic since the topic changes every week.

3.6) 2.5 I have been able to contact staff about this course when I needed to.

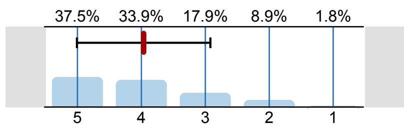
Definitely Agree


Definitely Disagree

n=50
av.=4.5
dev.=0.6
ab.=6
cf=94.00%

Please show the extent of your agreement by selecting the box that reflects your current view of your experience on this course to date:

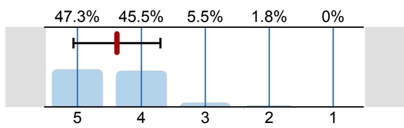
3.7) 2.6 The criteria used in marking have been clear in advance.

Definitely Agree


Definitely Disagree

n=56
av.=4
dev.=1
cf=71.43%

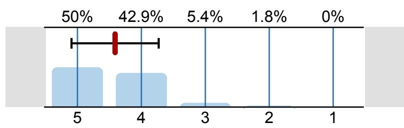
3.8) 2.7 Marking and assessment has been fair.

Definitely Agree


Definitely Disagree

n=55
av.=4.4
dev.=0.7
ab.=1
cf=92.73%

3.9) 2.8 The feedback I received has helped my learning and performance on the course.

Definitely Agree


Definitely Disagree

n=56
av.=4.4
dev.=0.7
cf=92.86%

3.10) 2.9 Do you have a reading list for this course?

Yes	33.9%	n=56
No	66.1%	

3.11) 2.9b The reading list(s) was useful for my learning.

Definitely Agree	5	4	3	2	1	Definitely Disagree	
	44.4%	27.8%	16.7%	11.1%	0%		n=18 av.=4.1 dev.=1.1 ab.=1 cf=72.22%

3.12) 2.9c I have been able to access all my essential readings for this course.

Definitely Agree	5	4	3	2	1	Definitely Disagree	
	61.1%	30.6%	5.6%	2.8%	0%		n=36 av.=4.5 dev.=0.7 ab.=20

3.13) 2.9d I have been able to access all my further readings for this course.

Definitely Agree	5	4	3	2	1	Definitely Disagree	
	46.7%	36.7%	13.3%	3.3%	0%		n=30 av.=4.3 dev.=0.8 ab.=25

3.14) 2.10 I found course materials and activities accessed through Moodle useful for my studies on this course.

Definitely Agree	5	4	3	2	1	Definitely Disagree	
	67.9%	28.3%	1.9%	1.9%	0%		n=53 av.=4.6 dev.=0.6 ab.=3 cf=96.23%

3.15) 2.11 The course material provided was useful for my studies and learning.

Definitely Agree	5	4	3	2	1	Definitely Disagree	
	58.5%	32.1%	7.5%	1.9%	0%		n=53 av.=4.5 dev.=0.7 ab.=3 cf=90.57%

3.16) 2.12 Do you have lectures for this course?

Yes	100%	n=55
No	0%	

3.17) 2.12b How are lectures delivered on this course:

face-to-face on-campus lectures	0%	n=55
live online lectures (e.g. via Zoom)	45.5%	
pre-recorded lectures	10.9%	
pre-recorded micro/short/mini lectures	1.8%	
pre-recorded lectures plus live Q&A	7.3%	
some combination of the above	34.5%	

3.18) 2.12c I am satisfied with the integration of classes/ seminars with lectures on this course.

Definitely Agree	5	4	3	2	1	Definitely Disagree	
	62.3%	32.1%	3.8%	1.9%	0%		n=53 av.=4.5 dev.=0.7

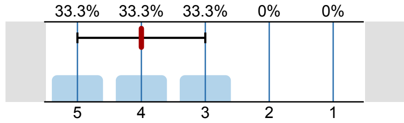
3.19) 2.13 Have you experienced on campus classroom teaching where some of the students are not physically in the classroom but participate via Zoom ('hybrid' classes)

Yes	5.5%	n=55
No	94.5%	

3.20) 2.13b Have you participated in these sessions

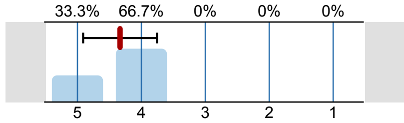
in the classroom	33.3%	n=3
via Zoom	66.7%	
both	0%	

3.21) 2.13c Overall, I am satisfied with the teaching in these ‘hybrid’ classes/seminars.

Definitely Agree  Definitely Disagree

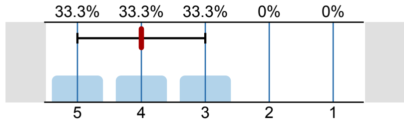
n=3
av.=4
dev.=1

3.22) 2.13d I have been able to participate actively in these classes/seminars.

Definitely Agree  Definitely Disagree

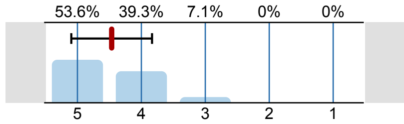
n=3
av.=4.3
dev.=0.6

3.23) 2.13e Thinking about the technologies used (audio, visual), these classes/seminars have worked well.

Definitely Agree  Definitely Disagree

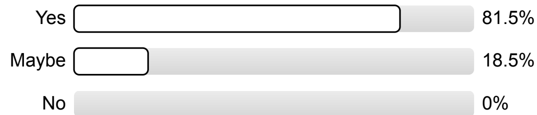
n=3
av.=4
dev.=1

3.25) 2.14 Overall, I am satisfied with my experience on this course.

Definitely Agree  Definitely Disagree

n=56
av.=4.5
dev.=0.6
cf=92.86%

3.26) 2.15 Would you recommend this course to other students?



n=54

3.27) 2.16 Please comment below on aspects of this course you think were particularly good.

- EC102 Live lectures are interesting and the lecturer often invite guest speakers who were all relevant to the course.
- Enjoyable topics
- Fun
- I particularly liked the way Ronny explained how to understand economic concepts which we learnt at A levels
- I really like the beginnings of lecture with several songs!
- It is an interesting course and stimulates intellectual thinking
- Moving lines on the diagrams are very useful for illustration and understnading purposes.
- Quiz, PS and particularly the extra-curricular Sets of questions.
- The amount of content is not too big/little. I enjoy having guest speakers in lectures as it links what we learn to the real world.
- The content is well organized. I have studied economics at a high school level and I find this course builds upon my background knowledge so that I don't waste my time.
- The course material is very interesting.
- The teaching method is full of logic and interest that atract me to focus.
- This course is really interesting and provides me insights into various topics into microeconomics. The use of examples in daily life helps me better understand the theories.
- professors and teachers all very motivated and involved
- relevance to real life examples and inviting guest lecturers.
- there is constant application to real life examples
- weekly lectures and problem sets and midweek tasks

3.28) 2.16b Please comment below on aspects of this course you think could be improved.

- Everything is fine!
- I think it’s overall good.

- More practice questions and maybe suggest some extra materials(readings..etc) for some topics
- N/A.
- No sure.
- None
- Nothing
- Nothing.
- Reading suggestions could be increased.
- lecture content could be delievered more clearly
- more material
- nil

4. Your Information

4.1) 3.1 Which of the reasons given below describe why you are taking the course? *(Please select all that apply)*

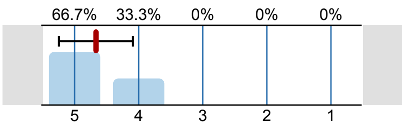
It is compulsory for my degree programme	91.1%	n=56
I chose the course as an option for my degree programme	5.4%	
I am interested in the subject matter	30.4%	
It was recommended to me by other students	1.8%	
It was recommended to me by an academic	1.8%	
Other	0%	

4.2) 3.1b Was this your 1st, 2nd, 3rd or other choice?

1st choice	100%	n=3
2nd choice	0%	
3rd choice	0%	
Other choice	0%	

4.3) 3.1c In relation to what you wanted to study, how important was choosing this course to you?

Very Important



Not at all Important

n=3
av.=4.7
dev.=0.6

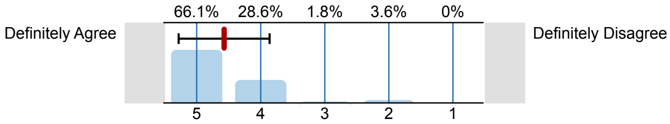
4.4) 3.2 How many hours of independent study do you put into this course each week outside of lectures, classes, and seminars?

More than 10 hours	3.6%	n=55
6-10 hours	34.5%	
2-5 hours	56.4%	
Less than 2 hours	5.5%	
None	0%	
N/A	0%	

4.6) 3.4 Do you have an Inclusion Plan related to a declared disability?

Yes	0%	n=56
No	100%	

4.9) 3.5 Overall, I have not had problems with digital access to Moodle or other technologies throughout the term.



n=56
av.=4.6
dev.=0.7

Profile

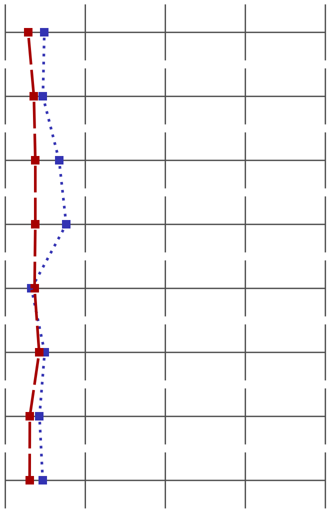
Compilation: Instructor profile

Comparative line: MT20 Economics Class Surveys

Values used in the profile line: Mean

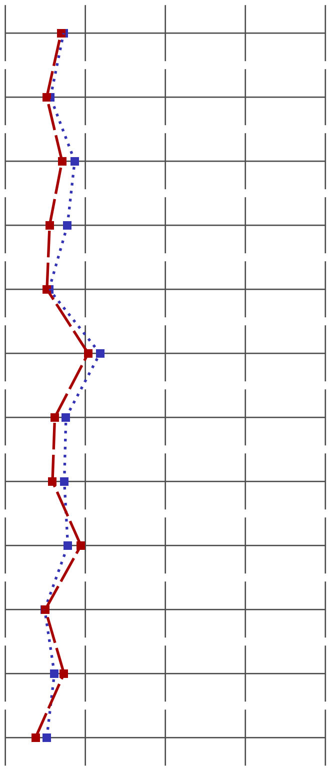
1. Class/Seminar Teacher Evaluation

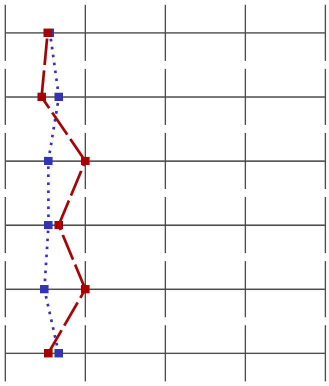
1.2)	1.1 The teacher communicated ideas and concepts effectively.	Definitely Agree	Definitely Disagree	n=56 n=2133	av.=4.7 av.=4.5
1.3)	1.2 The teacher has improved my understanding of the course content.	Definitely Agree	Definitely Disagree	n=56 n=2133	av.=4.6 av.=4.5
1.4)	1.3 The teacher has made the subject interesting.	Definitely Agree	Definitely Disagree	n=56 n=2132	av.=4.6 av.=4.3
1.6)	1.4b The teacher is good at involving members of the class/seminar.	Definitely Agree	Definitely Disagree	n=56 n=2124	av.=4.6 av.=4.2
1.8)	1.5b Feedback on my work has been timely (typically 3-4 weeks after submission).	Definitely Agree	Definitely Disagree	n=52 n=1686	av.=4.6 av.=4.7
1.9)	1.5c I have received helpful comments on my work.	Definitely Agree	Definitely Disagree	n=52 n=1682	av.=4.6 av.=4.5
1.10)	1.5d I was able to seek further clarification on feedback from the teacher where needed.	Definitely Agree	Definitely Disagree	n=49 n=1490	av.=4.7 av.=4.6
1.11)	1.6 Overall, I am satisfied with the class/seminar teaching by this teacher on this course.	Definitely Agree	Definitely Disagree	n=56 n=2134	av.=4.7 av.=4.5



3. Course Evaluation

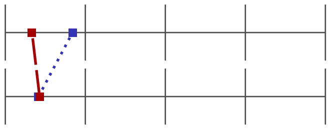
3.1)	2.1 This course has challenged me to achieve my best work.	Definitely Agree	Definitely Disagree	n=56 n=2134	av.=4.3 av.=4.3
3.2)	2.2 This course is intellectually stimulating.	Definitely Agree	Definitely Disagree	n=56 n=2134	av.=4.5 av.=4.4
3.3)	2.3 I have received sufficient advice and guidance in relation to this course to date.	Definitely Agree	Definitely Disagree	n=55 n=2117	av.=4.3 av.=4.1
3.4)	2.4 I am satisfied with the amount of contact time with teachers for this course.	Definitely Agree	Definitely Disagree	n=56 n=2122	av.=4.4 av.=4.2
3.6)	2.5 I have been able to contact staff about this course when I needed to.	Definitely Agree	Definitely Disagree	n=50 n=1931	av.=4.5 av.=4.5
3.7)	2.6 The criteria used in marking have been clear in advance.	Definitely Agree	Definitely Disagree	n=56 n=2029	av.=4.0 av.=3.8
3.8)	2.7 Marking and assessment has been fair.	Definitely Agree	Definitely Disagree	n=55 n=1925	av.=4.4 av.=4.2
3.9)	2.8 The feedback I received has helped my learning and performance on the course.	Definitely Agree	Definitely Disagree	n=56 n=1973	av.=4.4 av.=4.3
3.11)	2.9b The reading list(s) was useful for my learning.	Definitely Agree	Definitely Disagree	n=18 n=1153	av.=4.1 av.=4.2
3.12)	2.9c I have been able to access all my essential readings for this course.	Definitely Agree	Definitely Disagree	n=36 n=1662	av.=4.5 av.=4.5
3.13)	2.9d I have been able to access all my further readings for this course.	Definitely Agree	Definitely Disagree	n=30 n=1557	av.=4.3 av.=4.4
3.14)	2.10 I found course materials and activities accessed through Moodle useful for my studies on this course.	Definitely Agree	Definitely Disagree	n=53 n=2010	av.=4.6 av.=4.5





3.15)	2.11 The course material provided was useful for my studies and learning.	Definitely Agree	Definitely Disagree	n=53 n=2024	av.=4.5 av.=4.4
3.18)	2.12c I am satisfied with the integration of classes/ seminars with lectures on this course.	Definitely Agree	Definitely Disagree	n=53 n=2017	av.=4.5 av.=4.3
3.21)	2.13c Overall, I am satisfied with the teaching in these ‘hybrid’ classes/seminars.	Definitely Agree	Definitely Disagree	n=3 n=214	av.=4.0 av.=4.5
3.22)	2.13d I have been able to participate actively in these classes/seminars.	Definitely Agree	Definitely Disagree	n=3 n=215	av.=4.3 av.=4.5
3.23)	2.13e Thinking about the technologies used (audio, visual), these classes/seminars have worked well.	Definitely Agree	Definitely Disagree	n=3 n=211	av.=4.0 av.=4.5
3.25)	2.14 Overall, I am satisfied with my experience on this course.	Definitely Agree	Definitely Disagree	n=56 n=2134	av.=4.5 av.=4.3

4. Your Information



4.3)	3.1c In relation to what you wanted to study, how important was choosing this course to you?	Very Important	Not at all Important	n=3 n=513	av.=4.7 av.=4.2
4.9)	3.5 Overall, I have not had problems with digital access to Moodle or other technologies throughout the term.	Definitely Agree	Definitely Disagree	n=56 n=2120	av.=4.6 av.=4.6

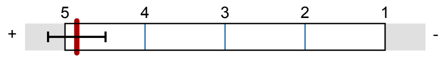
Ghassane Benmir
Instructor profile
No. of responses = 21

Overall indicators

Global Index

av.=4.7
dev.=0.5

Class/Seminar Teacher Evaluation (Scale width: 5)



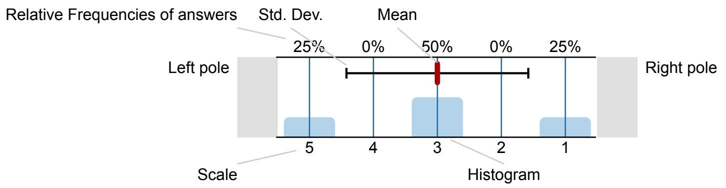
av.=4.9
dev.=0.4

Course Evaluation (Scale width: 5)

av.=4.6
dev.=0.6

Legend

Question text



n=No. of responses
av.=Mean
dev.=Std. Dev.
ab.=Abstention
cf=Cumulative Frequency

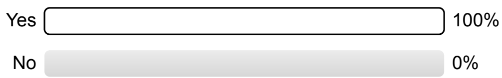
1. Class/Seminar Teacher Evaluation

This survey requests your feedback on two separate aspects of your learning experience, split into three sections. The first section asks for your views on your teacher’s class/seminar teaching. The second section asks for your views on the course as a whole at this point in time. Finally, the third section asks for some information about you, to aid analysis.

We recognise that this term has been particularly challenging for everyone due to the wider public health situation, with disruption experienced by both students and teaching staff. The School is continually striving to deliver the best possible educational experience despite these challenges and your views about your learning experience at LSE are a valuable source of information about this. The results will be used to help improve the teaching and learning experience for you and your peers and to identify good practice.

The School assumes that your response is broadly positive if you 'mostly agree' or 'definitely agree' with a statement.

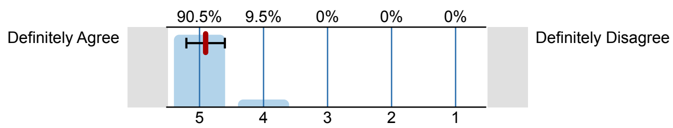
1.1) Do the answers you supply below relate to the teacher from whom you have received the majority of your class/seminar teaching this term? The teacher’s name, course title and group number (where relevant) are provided in the invitation email you have received for the survey.



n=19

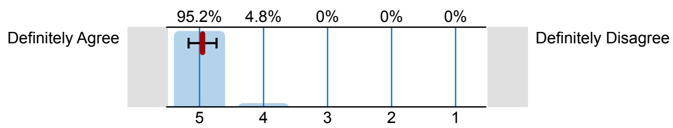
Please show the extent of your agreement by selecting the box that reflects your current view of your class/seminar teacher:

1.2) 1.1 The teacher communicated ideas and concepts effectively.



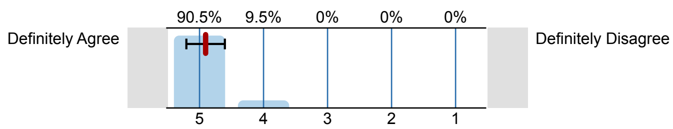
n=21
av.=4.9
dev.=0.3
cf=100.00%

1.3) 1.2 The teacher has improved my understanding of the course content.



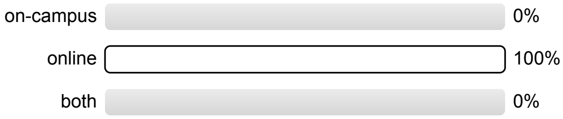
n=21
av.=5
dev.=0.2
cf=100.00%

1.4) 1.3 The teacher has made the subject interesting.



n=21
av.=4.9
dev.=0.3
cf=100.00%

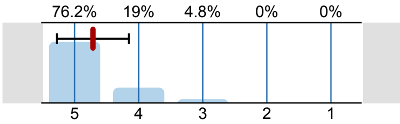
1.5) 1.4 Have you attended classes/seminars for this class/seminar:



n=21

1.6) 1.4b The teacher is good at involving members of the class/seminar.

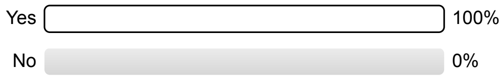
Definitely Agree



Definitely Disagree

n=21
av.=4.7
dev.=0.6
cf=95.24%

1.7) 1.5 Have you received feedback on your work from this teacher?

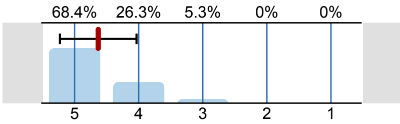


n=20

Please show the extent of your agreement by selecting the box that reflects your current view of your class/seminar teacher:

1.8) 1.5b Feedback on my work has been timely (typically 3-4 weeks after submission).

Definitely Agree

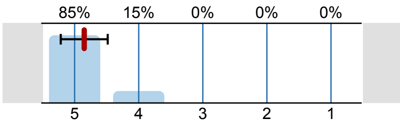


Definitely Disagree

n=19
av.=4.6
dev.=0.6
ab.=1
cf=94.74%

1.9) 1.5c I have received helpful comments on my work.

Definitely Agree

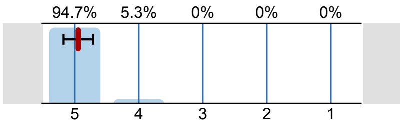


Definitely Disagree

n=20
av.=4.9
dev.=0.4
cf=100.00%

1.10) 1.5d I was able to seek further clarification on feedback from the teacher where needed.

Definitely Agree



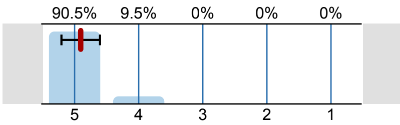
Definitely Disagree

n=19
av.=4.9
dev.=0.2
cf=100.00%

Please show the extent of your agreement by selecting the box that reflects your current view of your class/seminar teacher:

1.11) 1.6 Overall, I am satisfied with the class/seminar teaching by this teacher on this course.

Definitely Agree



Definitely Disagree

n=21
av.=4.9
dev.=0.3
cf=100.00%

1.12) 1.7 Please comment below on aspects of this teacher's class/seminar teaching you think were particularly helpful.

- Breaking down the comments and content into digestible parts and connecting them later.
- Ghassane clearly wants us students to excel in his class. He explains the concepts from a different perspective than the lecture so we have a sort of two dimensional understanding of the materials. If anyone does not understand a concept nevertheless, he takes the time to explain it in detail after class. He is always available when we reach out and happy to help out. An excellent teacher.
- He is very willing to give up his time to help us out. He did a 1 to 1 meeting with us to give personal feedback on our work.
- I feel like our teacher goes beyond what is expected of him. Compared to my other teachers I feel like I can always reach out to him and he will never stop explaining before I understand. He goes over the material in detail and an extra summary he prepares. He can find some extra time for office hour if we need it. The material was especially hard in the lent term for me, and he understands it and puts more effort compared to the last term.
- Plenty of office hours.
- Really well-structured lessons, content is broken down and made simpler by Ghassane. Would be happy to be taught again by him in the future.
- The summary at the beginning of each class is very helpful as it summarizes the whole content of the previous weeks, accompanied by detailed explanation. The fact that this was written to replicate the scenarios I'm the quiz/problem set is also helpful as we can use this throughout our class, relaxing some timing constraints. In addition, the teacher have tried his best to fit everything on time, following my comment on the Michaelmas term. So, this is another area of improvement worth mentioning.

1.13) 1.7b Please comment below on aspects of this teacher's class/seminar teaching you think could be improved.

- \-

- He is perfect!
- I think my teachers moodle was broken for a bit, didn't receive any feedback for a bit. Have received it now and was very useful
- Maybe it was because this year was online, but only a few people participated actively in the class throughout the year.
- Sometimes the handwriting was a bit difficult to read and some symbols are inconsistent with the lectures. Thus, it would be better if we could have different symbols aligned to avoid confusion.

2. Thank you - Part 1 Complete

Thank you for completing the teacher evaluation of the class/seminar survey.

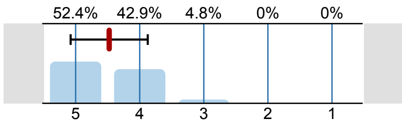
The next part of the survey asks for your views on the course as a whole. It is not restricted to this particular teacher, but to the entire experience you have had on this course to date.

3. Course Evaluation

Please show the extent of your agreement by selecting the box that reflects your current view of your experience on this course to date:

3.1) 2.1 This course has challenged me to achieve my best work.

Definitely Agree

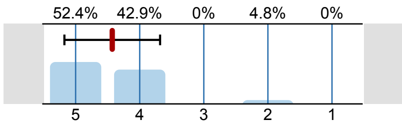


Definitely Disagree

n=21
av.=4.5
dev.=0.6
cf=95.24%

3.2) 2.2 This course is intellectually stimulating.

Definitely Agree

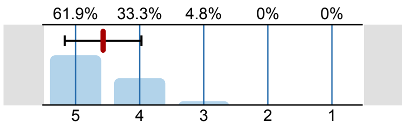


Definitely Disagree

n=21
av.=4.4
dev.=0.7
cf=95.24%

3.3) 2.3 I have received sufficient advice and guidance in relation to this course to date.

Definitely Agree

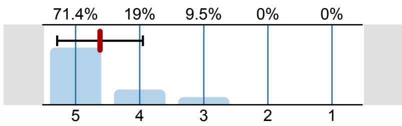


Definitely Disagree

n=21
av.=4.6
dev.=0.6
cf=95.24%

3.4) 2.4 I am satisfied with the amount of contact time with teachers for this course.

Definitely Agree

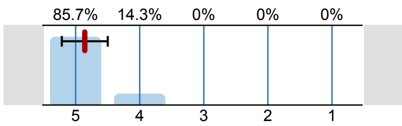


Definitely Disagree

n=21
av.=4.6
dev.=0.7
cf=90.48%

3.6) 2.5 I have been able to contact staff about this course when I needed to.

Definitely Agree



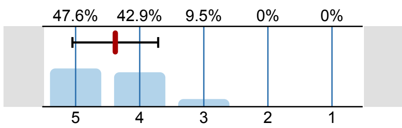
Definitely Disagree

n=21
av.=4.9
dev.=0.4
cf=100.00%

Please show the extent of your agreement by selecting the box that reflects your current view of your experience on this course to date:

3.7) 2.6 The criteria used in marking have been clear in advance.

Definitely Agree

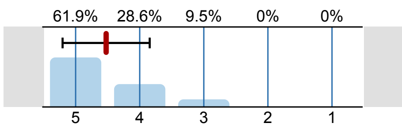


Definitely Disagree

n=21
av.=4.4
dev.=0.7
cf=90.48%

3.8) 2.7 Marking and assessment has been fair.

Definitely Agree

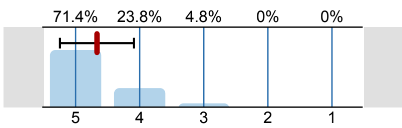


Definitely Disagree

n=21
av.=4.5
dev.=0.7
cf=90.48%

3.9) 2.8 The feedback I received has helped my learning and performance on the course.

Definitely Agree



Definitely Disagree

n=21
av.=4.7
dev.=0.6
cf=95.24%

3.10) 2.9 Do you have a reading list for this course?

Yes	19%	n=21
No	81%	

3.11) 2.9b The reading list(s) was useful for my learning.

Definitely Agree	5	4	3	2	1	Definitely Disagree	
	0%	75%	25%	0%	0%		n=4 av.=3.8 dev.=0.5 cf=75.00%

3.12) 2.9c I have been able to access all my essential readings for this course.

Definitely Agree	5	4	3	2	1	Definitely Disagree	
	68.8%	18.8%	12.5%	0%	0%		n=16 av.=4.6 dev.=0.7 ab.=5

3.13) 2.9d I have been able to access all my further readings for this course.

Definitely Agree	5	4	3	2	1	Definitely Disagree	
	62.5%	25%	12.5%	0%	0%		n=16 av.=4.5 dev.=0.7 ab.=5

3.14) 2.10 I found course materials and activities accessed through Moodle useful for my studies on this course.

Definitely Agree	5	4	3	2	1	Definitely Disagree	
	65%	30%	5%	0%	0%		n=20 av.=4.6 dev.=0.6 ab.=1 cf=95.00%

3.15) 2.11 The course material provided was useful for my studies and learning.

Definitely Agree	5	4	3	2	1	Definitely Disagree	
	75%	20%	5%	0%	0%		n=20 av.=4.7 dev.=0.6 ab.=1 cf=95.00%

3.16) 2.12 Do you have lectures for this course?

Yes	100%	n=20
No	0%	

3.17) 2.12b How are lectures delivered on this course:

face-to-face on-campus lectures	0%	n=19
live online lectures (e.g. via Zoom)	36.8%	
pre-recorded lectures	5.3%	
pre-recorded micro/short/mini lectures	0%	
pre-recorded lectures plus live Q&A	5.3%	
some combination of the above	52.6%	

3.18) 2.12c I am satisfied with the integration of classes/ seminars with lectures on this course.

Definitely Agree	5	4	3	2	1	Definitely Disagree	
	63.2%	31.6%	5.3%	0%	0%		n=19 av.=4.6 dev.=0.6 ab.=1

3.19) 2.13 Have you experienced on campus classroom teaching where some of the students are not physically in the classroom but participate via Zoom ('hybrid' classes)

Yes	0%	n=21
No	100%	

3.25) 2.14 Overall, I am satisfied with my experience on this course.

Definitely Agree	5	4	3	2	1	Definitely Disagree	
	57.1%	38.1%	4.8%	0%	0%		n=21 av.=4.5 dev.=0.6 cf=95.24%

3.26) 2.15 Would you recommend this course to other students?

Yes	84.2%	n=19
Maybe	15.8%	
No	0%	

3.27) 2.16 Please comment below on aspects of this course you think were particularly good.

- Everything
- Included pop culture references into the lectures and making the content relevant to current developments.
- The structure of the course is very well-organized as it continuously build on the materials of previous weeks, helping us revised throughout. Also, it helps made clear where the story starts and ends. The lecturer has also made the subject more interesting by trying to putting in the context of movie.
- This course helped me to construct a model rather than understanding an existing one. I feel I can now start from the beginning and construct an economic model by myself.
- putting together the whole model in the end and showing how using the model one can predict how different shocks affect the economy

3.28) 2.16b Please comment below on aspects of this course you think could be improved.

- In general, I found that the time in class is almost always not enough, particularly when the materials become more challenging. There are loads of questions that should be addressed and lots of contents to cover. This often leads to rushing towards the end of the class while we are covering problem sets, which is where most of the marks are allocated to. I believe that this is not the problem only to my teacher, so it would be more helpful if we could have more class time eg. 1.5 hours.
- Lent term material was so complicated. I think a textbook or a pre-prepared lecture note as a textbook would be very helpful.
- Less math plzz
- it would be great to get an overview of the different weeks in the beginning. in particular it would be great to know that the first weeks are individual concepts that are then all tied together in one model in the end because in the first weeks i was a bit confused about the connections between the different weeks and how this information could be used together - worked out in the end when the final model was introduce but would be great to get an overview in the beginning

4. Your Information

4.1) 3.1 Which of the reasons given below describe why you are taking the course? *(Please select all that apply)*

It is compulsory for my degree programme	85.7%	n=21
I chose the course as an option for my degree programme	4.8%	
I am interested in the subject matter	14.3%	
It was recommended to me by other students	4.8%	
It was recommended to me by an academic	0%	
Other	0%	

4.2) 3.1b Was this your 1st, 2nd, 3rd or other choice?

1st choice	0%	n=1
2nd choice	100%	
3rd choice	0%	
Other choice	0%	

4.3) 3.1c In relation to what you wanted to study, how important was choosing this course to you?

	5	4	3	2	1		
Very Important	0%	100%	0%	0%	0%	Not at all Important	n=1 av.=4 dev.=0

4.4) 3.2 How many hours of independent study do you put into this course each week outside of lectures, classes, and seminars?

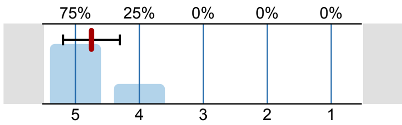
More than 10 hours	15%	n=20
6-10 hours	35%	
2-5 hours	40%	
Less than 2 hours	10%	
None	0%	
N/A	0%	

4.6) 3.4 Do you have an Inclusion Plan related to a declared disability?

Yes	0%	n=20
No	100%	

4.9) 3.5 Overall, I have not had problems with digital access to Moodle or other technologies throughout the term.

Definitely Agree



Definitely Disagree

n=20
av.=4.8
dev.=0.4

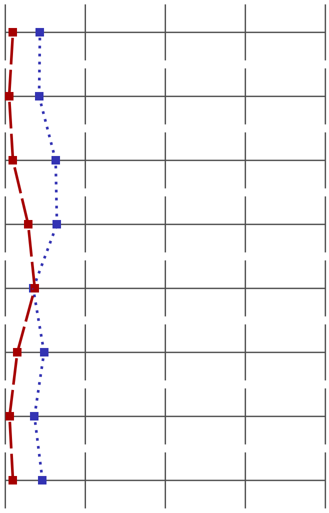
Profile

Compilation: Instructor profile

Comparative line: LT21 - Class Survey Economics

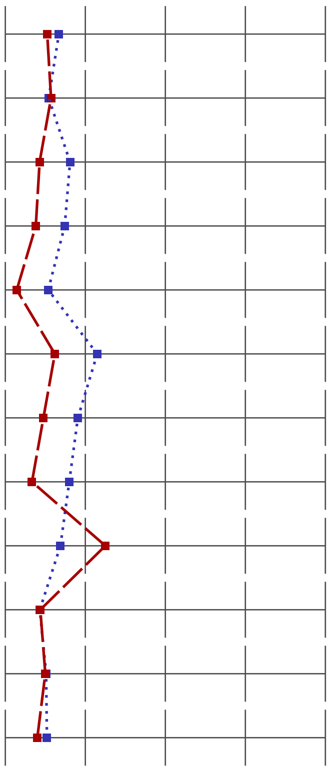
Values used in the profile line: Mean

1. Class/Seminar Teacher Evaluation

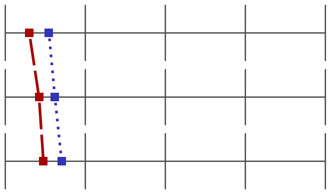


	Item	Left pole	Right pole	n (Instructor profile)	av. (Instructor profile)	n (LT21 - Class Survey Economics)	av. (LT21 - Class Survey Economics)
1.2)	1.1 The teacher communicated ideas and concepts effectively.	Definitely Agree	Definitely Disagree	n=21	av.=4.9	n=2032	av.=4.6
1.3)	1.2 The teacher has improved my understanding of the course content.	Definitely Agree	Definitely Disagree	n=21	av.=5.0	n=2032	av.=4.6
1.4)	1.3 The teacher has made the subject interesting.	Definitely Agree	Definitely Disagree	n=21	av.=4.9	n=2032	av.=4.4
1.6)	1.4b The teacher is good at involving members of the class/seminar.	Definitely Agree	Definitely Disagree	n=21	av.=4.7	n=2026	av.=4.4
1.8)	1.5b Feedback on my work has been timely (typically 3-4 weeks after submission).	Definitely Agree	Definitely Disagree	n=19	av.=4.6	n=1551	av.=4.7
1.9)	1.5c I have received helpful comments on my work.	Definitely Agree	Definitely Disagree	n=20	av.=4.9	n=1543	av.=4.5
1.10)	1.5d I was able to seek further clarification on feedback from the teacher where needed.	Definitely Agree	Definitely Disagree	n=19	av.=4.9	n=1386	av.=4.6
1.11)	1.6 Overall, I am satisfied with the class/seminar teaching by this teacher on this course.	Definitely Agree	Definitely Disagree	n=21	av.=4.9	n=2034	av.=4.5

3. Course Evaluation

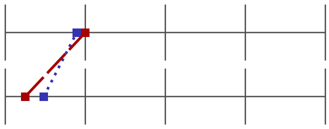


	Item	Left pole	Right pole	n (Instructor profile)	av. (Instructor profile)	n (LT21 - Class Survey Economics)	av. (LT21 - Class Survey Economics)
3.1)	2.1 This course has challenged me to achieve my best work.	Definitely Agree	Definitely Disagree	n=21	av.=4.5	n=2031	av.=4.3
3.2)	2.2 This course is intellectually stimulating.	Definitely Agree	Definitely Disagree	n=21	av.=4.4	n=2033	av.=4.5
3.3)	2.3 I have received sufficient advice and guidance in relation to this course to date.	Definitely Agree	Definitely Disagree	n=21	av.=4.6	n=2020	av.=4.2
3.4)	2.4 I am satisfied with the amount of contact time with teachers for this course.	Definitely Agree	Definitely Disagree	n=21	av.=4.6	n=2022	av.=4.3
3.6)	2.5 I have been able to contact staff about this course when I needed to.	Definitely Agree	Definitely Disagree	n=21	av.=4.9	n=1873	av.=4.5
3.7)	2.6 The criteria used in marking have been clear in advance.	Definitely Agree	Definitely Disagree	n=21	av.=4.4	n=1965	av.=3.9
3.8)	2.7 Marking and assessment has been fair.	Definitely Agree	Definitely Disagree	n=21	av.=4.5	n=1885	av.=4.1
3.9)	2.8 The feedback I received has helped my learning and performance on the course.	Definitely Agree	Definitely Disagree	n=21	av.=4.7	n=1872	av.=4.2
3.11)	2.9b The reading list(s) was useful for my learning.	Definitely Agree	Definitely Disagree	n=4	av.=3.8	n=1176	av.=4.3
3.12)	2.9c I have been able to access all my essential readings for this course.	Definitely Agree	Definitely Disagree	n=16	av.=4.6	n=1635	av.=4.6
3.13)	2.9d I have been able to access all my further readings for this course.	Definitely Agree	Definitely Disagree	n=16	av.=4.5	n=1555	av.=4.5
3.14)	2.10 I found course materials and activities accessed through Moodle useful for my studies on this course.	Definitely Agree	Definitely Disagree	n=20	av.=4.6	n=1919	av.=4.5



3.15)	2.11 The course material provided was useful for my studies and learning.	Definitely Agree	Definitely Disagree	n=20 n=1932	av.=4.7 av.=4.5
3.18)	2.12c I am satisfied with the integration of classes/ seminars with lectures on this course.	Definitely Agree	Definitely Disagree	n=19 n=1953	av.=4.6 av.=4.4
3.25)	2.14 Overall, I am satisfied with my experience on this course.	Definitely Agree	Definitely Disagree	n=21 n=2034	av.=4.5 av.=4.3

4. Your Information



4.3)	3.1c In relation to what you wanted to study, how important was choosing this course to you?	Very Important	Not at all Important	n=1 n=603	av.=4.0 av.=4.1
4.9)	3.5 Overall, I have not had problems with digital access to Moodle or other technologies throughout the term.	Definitely Agree	Definitely Disagree	n=20 n=2016	av.=4.8 av.=4.5

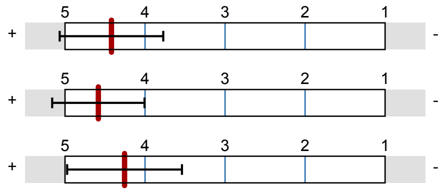
Ghassane Benmir
EC1A3.A Microeconomics I - Group 8
No. of responses = 8

Overall indicators

Global Index

Class/Seminar Teacher Evaluation (Scale width: 5)

Course Evaluation (Scale width: 5)



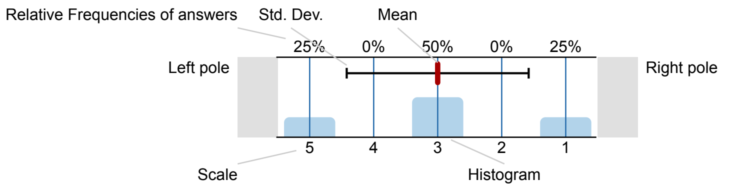
av.=4.4
dev.=0.6

av.=4.6
dev.=0.6

av.=4.3
dev.=0.7

Legend

Question text



n=No. of responses
av.=Mean
dev.=Std. Dev.
ab.=Abstention
cf=Cumulative Frequency

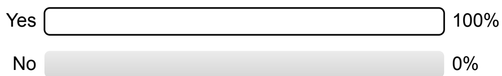
1. Class/Seminar Teacher Evaluation

This survey requests your feedback on two separate aspects of your learning experience, split into three sections. The first section asks for your views on your teacher's class/seminar teaching. The second section asks for your views on the course as a whole at this point in time. Finally, the third section asks for some information about you, to aid analysis.

We recognise that this term has been particularly challenging for everyone due to the wider public health situation, with disruption experienced by both students and teaching staff. The School is continually striving to deliver the best possible educational experience despite these challenges and your views about your learning experience at LSE are a valuable source of information about this. The results will be used to help improve the teaching and learning experience for you and your peers and to identify good practice.

The School assumes that your response is broadly positive if you 'mostly agree' or 'definitely agree' with a statement.

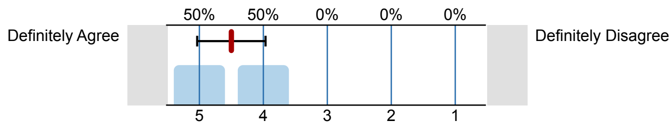
1.1) Do the answers you supply below relate to the teacher from whom you have received the majority of your class/seminar teaching this term? The teacher's name, course title and group number (where relevant) are provided in the invitation email you have received for the survey.



n=8

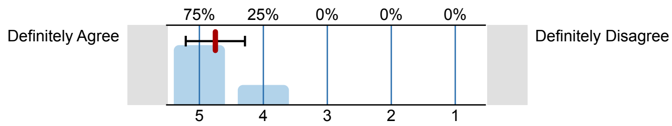
Please show the extent of your agreement by selecting the box that reflects your current view of your class/seminar teacher:

1.2) 1.1 The teacher communicated ideas and concepts effectively.



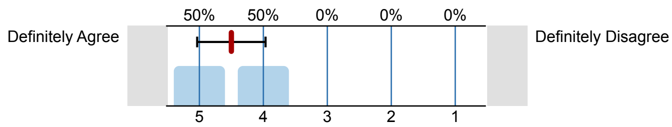
n=8
av.=4.5
dev.=0.5
cf=100.00%

1.3) 1.2 The teacher has improved my understanding of the course content.



n=8
av.=4.8
dev.=0.5
cf=100.00%

1.4) 1.3 The teacher has made the subject interesting.

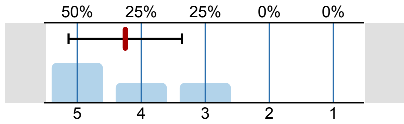


n=8
av.=4.5
dev.=0.5
cf=100.00%

1.5) 1.4 Have you attended classes/seminars for this class/seminar:

on-campus	100%	n=8
online	0%	
both	0%	

1.6) 1.4b The teacher is good at involving members of the class/seminar.

Definitely Agree  Definitely Disagree

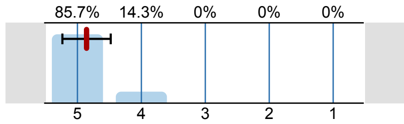
n=8
av.=4.3
dev.=0.9
cf=75.00%

1.7) 1.5 Have you received feedback on your work from this teacher?

Yes	100%	n=7
No	0%	

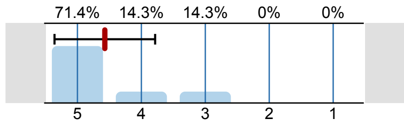
Please show the extent of your agreement by selecting the box that reflects your current view of your class/seminar teacher:

1.8) 1.5b Feedback on my work has been timely (typically 3-4 weeks after submission).

Definitely Agree  Definitely Disagree

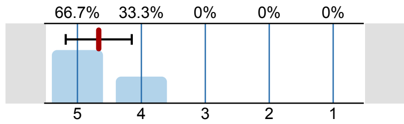
n=7
av.=4.9
dev.=0.4
cf=100.00%

1.9) 1.5c I have received helpful comments on my work.

Definitely Agree  Definitely Disagree

n=7
av.=4.6
dev.=0.8
cf=85.71%

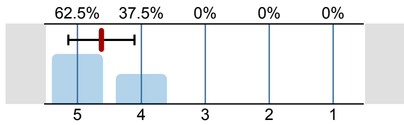
1.10) 1.5d I was able to seek further clarification on feedback from the teacher where needed.

Definitely Agree  Definitely Disagree

n=6
av.=4.7
dev.=0.5
ab.=1
cf=100.00%

Please show the extent of your agreement by selecting the box that reflects your current view of your class/seminar teacher:

1.11) 1.6 Overall, I am satisfied with the class/seminar teaching by this teacher on this course.

Definitely Agree  Definitely Disagree

n=8
av.=4.6
dev.=0.5
cf=100.00%

1.12) 1.7 Please comment below on aspects of this teacher's class/seminar teaching you think were particularly helpful.

- I enjoy the way the class is delivered, keeps the content interesting

2. Thank you - Part 1 Complete

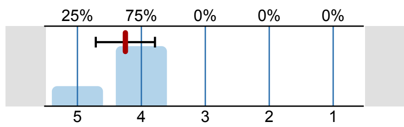
Thank you for completing the teacher evaluation of the class/seminar survey.

The next part of the survey asks for your views on the course as a whole. It is not restricted to this particular teacher, but to the entire experience you have had on this course to date.

3. Course Evaluation

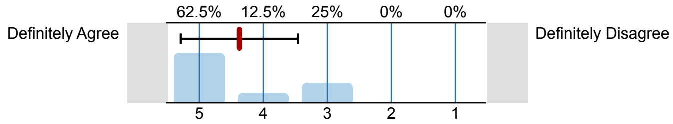
Please show the extent of your agreement by selecting the box that reflects your current view of your experience on this course to date:

3.1) 2.1 This course has challenged me to achieve my best work.

Definitely Agree  Definitely Disagree

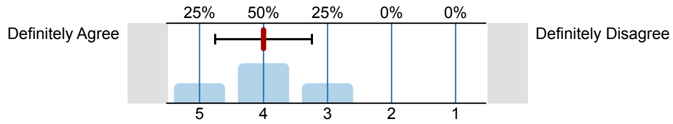
n=8
av.=4.3
dev.=0.5
cf=100.00%

3.2) 2.2 This course is intellectually stimulating.



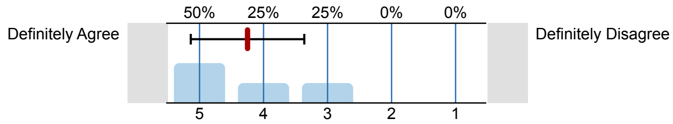
n=8
av.=4.4
dev.=0.9
cf=75.00%

3.3) 2.3 I have received sufficient advice and guidance in relation to this course to date.



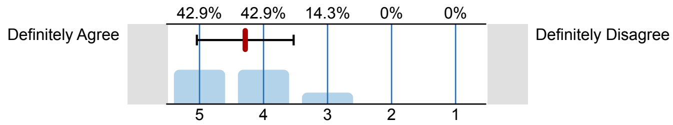
n=8
av.=4
dev.=0.8
cf=75.00%

3.4) 2.4 I am satisfied with the amount of contact time with teachers for this course.



n=8
av.=4.3
dev.=0.9
cf=75.00%

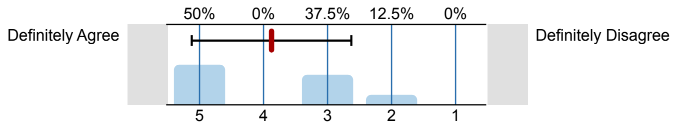
3.6) 2.5 I have been able to contact staff about this course when I needed to.



n=7
av.=4.3
dev.=0.8
ab.=1
cf=85.71%

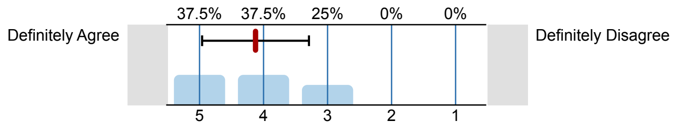
Please show the extent of your agreement by selecting the box that reflects your current view of your experience on this course to date:

3.7) 2.6 The criteria used in marking have been clear in advance.



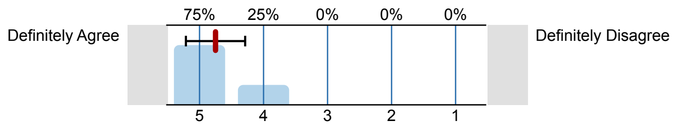
n=8
av.=3.9
dev.=1.2
cf=50.00%

3.8) 2.7 Marking and assessment has been fair.



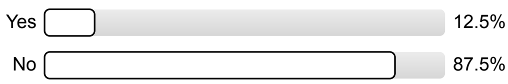
n=8
av.=4.1
dev.=0.8
cf=75.00%

3.9) 2.8 The feedback I received has helped my learning and performance on the course.



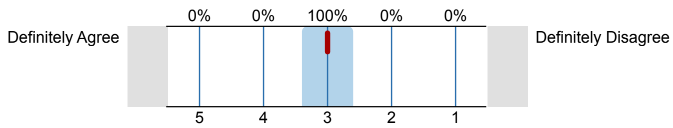
n=8
av.=4.8
dev.=0.5
cf=100.00%

3.10) 2.9 Do you have a reading list for this course?



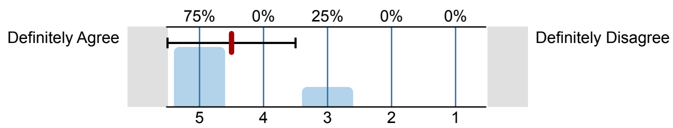
n=8

3.11) 2.9b The reading list(s) was useful for my learning.



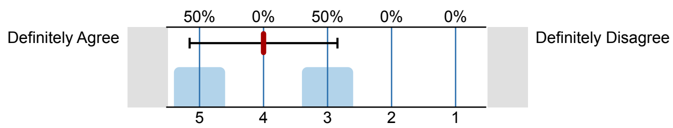
n=1
av.=3
dev.=0
cf=0.00%

3.12) 2.9c I have been able to access all my essential readings for this course.



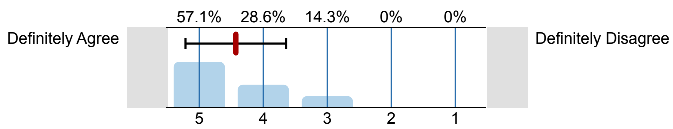
n=4
av.=4.5
dev.=1
ab.=4
cf=75.00%

3.13) 2.9d I have been able to access all my further readings for this course.



n=4
av.=4
dev.=1.2
ab.=4
cf=50.00%

3.14) 2.10 I found course materials and activities accessed through Moodle useful for my studies on this course.



n=7
av.=4.4
dev.=0.8
ab.=1
cf=85.71%

3.15) 2.11 The course material provided was useful for my studies and learning.

Definitely Agree	5	4	3	2	1	Definitely Disagree
	42.9%	42.9%	14.3%	0%	0%	

n=7
av.=4.3
dev.=0.8
ab.=1
cf=85.71%

3.16) 2.12 Do you have lectures for this course?

Yes	100%	n=8
No	0%	

3.17) 2.12b How are lectures delivered on this course:

face-to-face on-campus lectures	0%	n=8
live online lectures (e.g. via Zoom)	87.5%	
pre-recorded lectures	0%	
pre-recorded micro/short/mini lectures	0%	
pre-recorded lectures plus live Q&A	0%	
some combination of the above	12.5%	

3.18) 2.12c I am satisfied with the integration of classes/ seminars with lectures on this course.

Definitely Agree	5	4	3	2	1	Definitely Disagree
	50%	50%	0%	0%	0%	

n=8
av.=4.5
dev.=0.5
cf=100.00%

3.19) 2.13 Have you experienced on campus classroom teaching where some of the students are not physically in the classroom but participate via Zoom (‘hybrid’ classes)

Yes	12.5%	n=8
No	87.5%	

3.20) 2.13b Have you participated in these sessions

in the classroom	100%	n=1
via Zoom	0%	
both	0%	

3.21) 2.13c Overall, I am satisfied with the teaching in these ‘hybrid’ classes/seminars.

Definitely Agree	5	4	3	2	1	Definitely Disagree
	100%	0%	0%	0%	0%	

n=1
av.=5
dev.=0
cf=100.00%

3.22) 2.13d I have been able to participate actively in these classes/seminars.

Definitely Agree	5	4	3	2	1	Definitely Disagree
	100%	0%	0%	0%	0%	

n=1
av.=5
dev.=0
cf=100.00%

3.23) 2.13e Thinking about the technologies used (audio, visual), these classes/seminars have worked well.

Definitely Agree	5	4	3	2	1	Definitely Disagree
	100%	0%	0%	0%	0%	

n=1
av.=5
dev.=0
cf=100.00%

3.25) 2.14 Overall, I am satisfied with my experience on this course.

Definitely Agree	5	4	3	2	1	Definitely Disagree
	50%	37.5%	12.5%	0%	0%	

n=8
av.=4.4
dev.=0.7
cf=87.50%

3.26) 2.15 Would you recommend this course to other students?

Yes	37.5%	n=8
Maybe	50%	
No	12.5%	

3.27) 2.16 Please comment below on aspects of this course you think were particularly good.

- interesting ties to various case studies, and applying things learnt to them

3.28) 2.16b Please comment below on aspects of this course you think could be improved.

- better integration at the start of the course, felt as though we were thrown straight into the deep end and left to figure it out for ourselves

4. Your Information

4.1) 3.1 Which of the reasons given below describe why you are taking the course? *(Please select all that apply)*

It is compulsory for my degree programme	87.5%	n=8
I chose the course as an option for my degree programme	12.5%	
I am interested in the subject matter	12.5%	
It was recommended to me by other students	0%	
It was recommended to me by an academic	0%	
Other	0%	

4.2) 3.1b Was this your 1st, 2nd, 3rd or other choice?

1st choice	0%	n=1
2nd choice	100%	
3rd choice	0%	
Other choice	0%	

4.3) 3.1c In relation to what you wanted to study, how important was choosing this course to you?

Very Important	5	4	3	2	1	Not at all Important	
	0%	100%	0%	0%	0%		n=1 av.=4 dev.=0 cf=100.00%

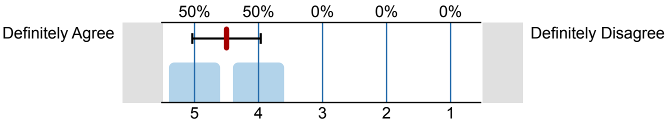
4.4) 3.2 How many hours of independent study do you put into this course each week outside of lectures, classes, and seminars?

More than 10 hours	12.5%	n=8
6-10 hours	0%	
2-5 hours	87.5%	
Less than 2 hours	0%	
None	0%	
N/A	0%	

4.6) 3.4 Do you have any Teaching and Learning Adjustments related to a declared disability?

Yes	0%	n=8
No	100%	

4.9) 3.5 Overall, I have not had problems with digital access to Moodle or other technologies throughout the term.



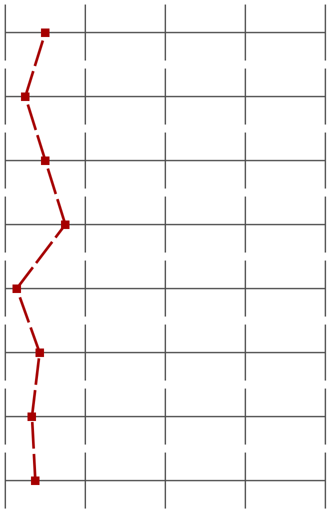
n=8
av.=4.5
dev.=0.5
cf=100.00%

Profile

Subunit: EC - Economics
Name of the instructor: Ghassane Benmir
Name of the course: (Name of the survey) EC1A3.A Microeconomics I - Group 8

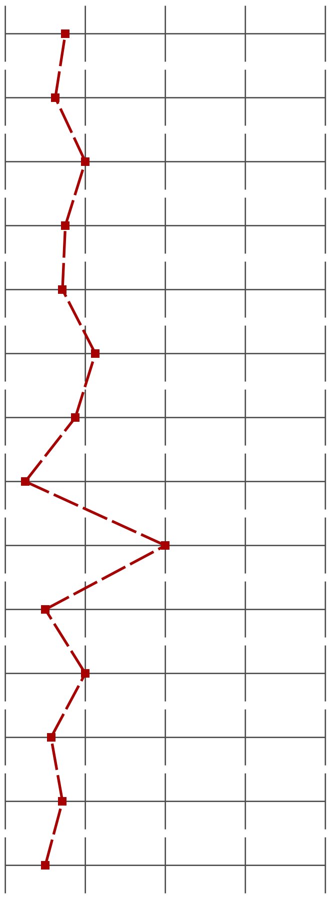
Values used in the profile line: Mean

1. Class/Seminar Teacher Evaluation



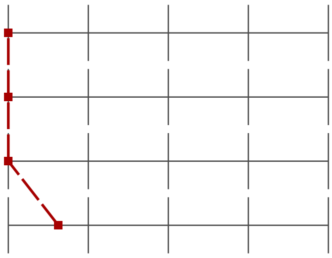
1.2)	1.1 The teacher communicated ideas and concepts effectively.	Definitely Agree	Definitely Disagree	n=8	av.=4.5
1.3)	1.2 The teacher has improved my understanding of the course content.	Definitely Agree	Definitely Disagree	n=8	av.=4.8
1.4)	1.3 The teacher has made the subject interesting.	Definitely Agree	Definitely Disagree	n=8	av.=4.5
1.6)	1.4b The teacher is good at involving members of the class/seminar.	Definitely Agree	Definitely Disagree	n=8	av.=4.3
1.8)	1.5b Feedback on my work has been timely (typically 3-4 weeks after submission).	Definitely Agree	Definitely Disagree	n=7	av.=4.9
1.9)	1.5c I have received helpful comments on my work.	Definitely Agree	Definitely Disagree	n=7	av.=4.6
1.10)	1.5d I was able to seek further clarification on feedback from the teacher where needed.	Definitely Agree	Definitely Disagree	n=6	av.=4.7
1.11)	1.6 Overall, I am satisfied with the class/seminar teaching by this teacher on this course.	Definitely Agree	Definitely Disagree	n=8	av.=4.6

3. Course Evaluation



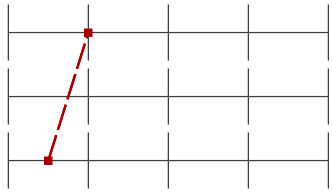
3.1)	2.1 This course has challenged me to achieve my best work.	Definitely Agree	Definitely Disagree	n=8	av.=4.3
3.2)	2.2 This course is intellectually stimulating.	Definitely Agree	Definitely Disagree	n=8	av.=4.4
3.3)	2.3 I have received sufficient advice and guidance in relation to this course to date.	Definitely Agree	Definitely Disagree	n=8	av.=4.0
3.4)	2.4 I am satisfied with the amount of contact time with teachers for this course.	Definitely Agree	Definitely Disagree	n=8	av.=4.3
3.6)	2.5 I have been able to contact staff about this course when I needed to.	Definitely Agree	Definitely Disagree	n=7	av.=4.3
3.7)	2.6 The criteria used in marking have been clear in advance.	Definitely Agree	Definitely Disagree	n=8	av.=3.9
3.8)	2.7 Marking and assessment has been fair.	Definitely Agree	Definitely Disagree	n=8	av.=4.1
3.9)	2.8 The feedback I received has helped my learning and performance on the course.	Definitely Agree	Definitely Disagree	n=8	av.=4.8
3.11)	2.9b The reading list(s) was useful for my learning.	Definitely Agree	Definitely Disagree	n=1	av.=3.0
3.12)	2.9c I have been able to access all my essential readings for this course.	Definitely Agree	Definitely Disagree	n=4	av.=4.5
3.13)	2.9d I have been able to access all my further readings for this course.	Definitely Agree	Definitely Disagree	n=4	av.=4.0
3.14)	2.10 I found course materials and activities accessed through Moodle useful for my studies on this course.	Definitely Agree	Definitely Disagree	n=7	av.=4.4
3.15)	2.11 The course material provided was useful for my studies and learning.	Definitely Agree	Definitely Disagree	n=7	av.=4.3
3.18)	2.12c I am satisfied with the integration of classes/ seminars with lectures on this course.	Definitely Agree	Definitely Disagree	n=8	av.=4.5

3.21)	2.13c Overall, I am satisfied with the teaching in these ‘hybrid’ classes/seminars.	Definitely Agree	Definitely Disagree	n=1	av.=5.0
3.22)	2.13d I have been able to participate actively in these classes/seminars.	Definitely Agree	Definitely Disagree	n=1	av.=5.0
3.23)	2.13e Thinking about the technologies used (audio, visual), these classes/seminars have worked well.	Definitely Agree	Definitely Disagree	n=1	av.=5.0
3.25)	2.14 Overall, I am satisfied with my experience on this course.	Definitely Agree	Definitely Disagree	n=8	av.=4.4



4. Your Information

4.3)	3.1c In relation to what you wanted to study, how important was choosing this course to you?	Very Important	Not at all Important	n=1	av.=4.0
4.5)	3.3 Please rate your own contribution to classes/ seminars. (*)	Very Good	Poor		
4.9)	3.5 Overall, I have not had problems with digital access to Moodle or other technologies throughout the term.	Definitely Agree	Definitely Disagree	n=8	av.=4.5



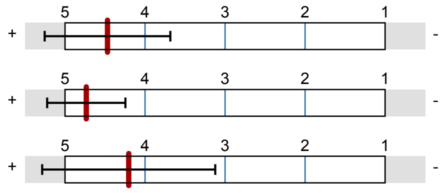
Ghassane Benmir
EC1A3.A Microeconomics I - Group 9
No. of responses = 10

Overall indicators

Global Index

Class/Seminar Teacher Evaluation (Scale width: 5)

Course Evaluation (Scale width: 5)



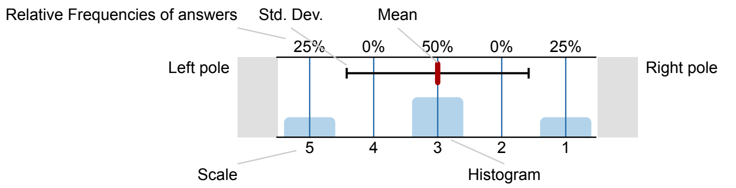
av.=4.5
dev.=0.8

av.=4.7
dev.=0.5

av.=4.2
dev.=1.1

Legend

Question text



n=No. of responses
av.=Mean
dev.=Std. Dev.
ab.=Abstention
cf=Cumulative Frequency

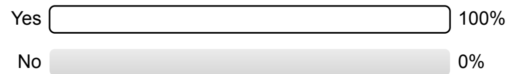
1. Class/Seminar Teacher Evaluation

This survey requests your feedback on two separate aspects of your learning experience, split into three sections. The first section asks for your views on your teacher’s class/seminar teaching. The second section asks for your views on the course as a whole at this point in time. Finally, the third section asks for some information about you, to aid analysis.

We recognise that this term has been particularly challenging for everyone due to the wider public health situation, with disruption experienced by both students and teaching staff. The School is continually striving to deliver the best possible educational experience despite these challenges and your views about your learning experience at LSE are a valuable source of information about this. The results will be used to help improve the teaching and learning experience for you and your peers and to identify good practice.

The School assumes that your response is broadly positive if you 'mostly agree' or 'definitely agree' with a statement.

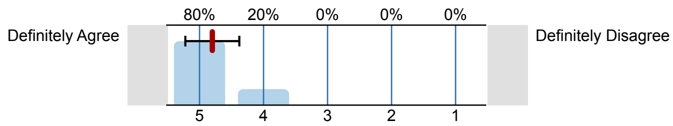
1.1) Do the answers you supply below relate to the teacher from whom you have received the majority of your class/seminar teaching this term? The teacher’s name, course title and group number (where relevant) are provided in the invitation email you have received for the survey.



n=10

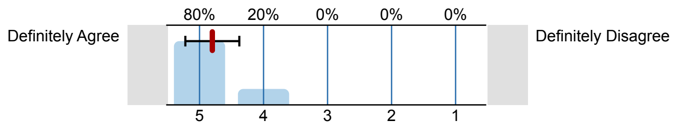
Please show the extent of your agreement by selecting the box that reflects your current view of your class/seminar teacher:

1.2) 1.1 The teacher communicated ideas and concepts effectively.



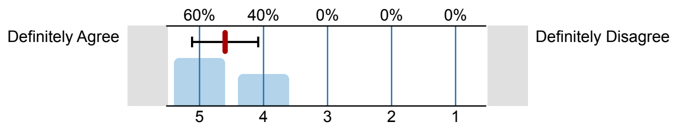
n=10
av.=4.8
dev.=0.4
cf=100.00%

1.3) 1.2 The teacher has improved my understanding of the course content.



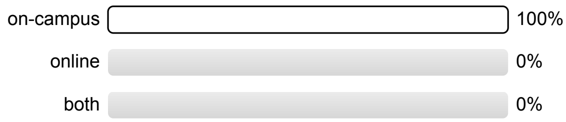
n=10
av.=4.8
dev.=0.4
cf=100.00%

1.4) 1.3 The teacher has made the subject interesting.



n=10
av.=4.6
dev.=0.5
cf=100.00%

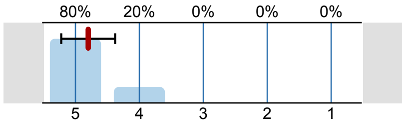
1.5) 1.4 Have you attended classes/seminars for this class/seminar:



n=10

1.6) 1.4b The teacher is good at involving members of the class/seminar.

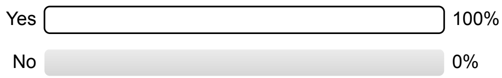
Definitely Agree



Definitely Disagree

n=10
av.=4.8
dev.=0.4
cf=100.00%

1.7) 1.5 Have you received feedback on your work from this teacher?

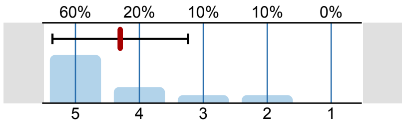


n=10

Please show the extent of your agreement by selecting the box that reflects your current view of your class/seminar teacher:

1.8) 1.5b Feedback on my work has been timely (typically 3-4 weeks after submission).

Definitely Agree

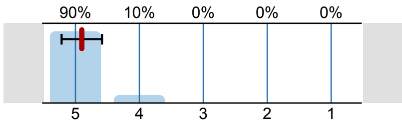


Definitely Disagree

n=10
av.=4.3
dev.=1.1
cf=80.00%

1.9) 1.5c I have received helpful comments on my work.

Definitely Agree

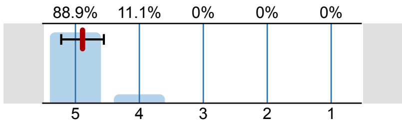


Definitely Disagree

n=10
av.=4.9
dev.=0.3
cf=100.00%

1.10) 1.5d I was able to seek further clarification on feedback from the teacher where needed.

Definitely Agree



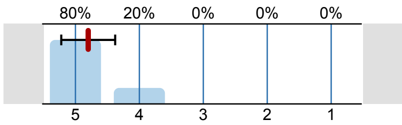
Definitely Disagree

n=9
av.=4.9
dev.=0.3
ab.=1
cf=100.00%

Please show the extent of your agreement by selecting the box that reflects your current view of your class/seminar teacher:

1.11) 1.6 Overall, I am satisfied with the class/seminar teaching by this teacher on this course.

Definitely Agree



Definitely Disagree

n=10
av.=4.8
dev.=0.4
cf=100.00%

1.12) 1.7 Please comment below on aspects of this teacher's class/seminar teaching you think were particularly helpful.

- -Makes sure everyone understands the conept before moving on
- Going over the examples from the problem set and discussing how marking will work is helpful.
- Great at explaining things.
- Thoroughly runs through weekly material.

1.13) 1.7b Please comment below on aspects of this teacher's class/seminar teaching you think could be improved.

- Some examples used aren’t relevant/ are sort of different or opposite to some of the examples in the course. Also just generally speaking, this overall course can be made a lot better, especially in comparison to the overall Econ department Econ course.

2. Thank you - Part 1 Complete

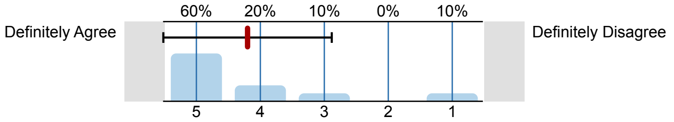
Thank you for completing the teacher evaluation of the class/seminar survey.

The next part of the survey asks for your views on the course as a whole. It is not restricted to this particular teacher, but to the entire experience you have had on this course to date.

3. Course Evaluation

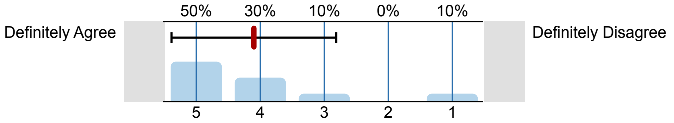
Please show the extent of your agreement by selecting the box that reflects your current view of your experience on this course to date:

3.1) 2.1 This course has challenged me to achieve my best work.



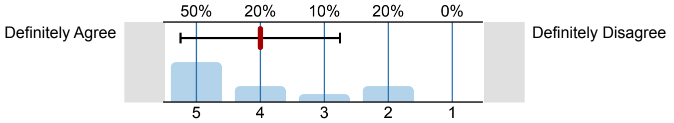
n=10
av.=4.2
dev.=1.3
cf=80.00%

3.2) 2.2 This course is intellectually stimulating.



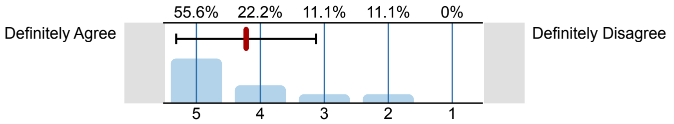
n=10
av.=4.1
dev.=1.3
cf=80.00%

3.3) 2.3 I have received sufficient advice and guidance in relation to this course to date.



n=10
av.=4
dev.=1.2
cf=70.00%

3.4) 2.4 I am satisfied with the amount of contact time with teachers for this course.

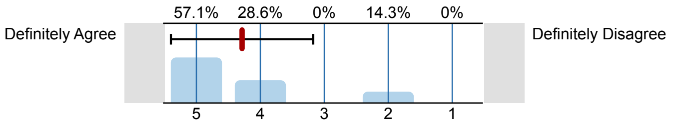


n=9
av.=4.2
dev.=1.1
ab.=1
cf=77.78%

3.5) 2.4b Please comment below about why contact time with teachers has been less than satisfactory.

- Need more.

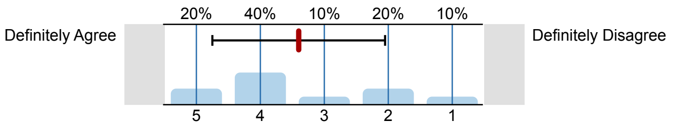
3.6) 2.5 I have been able to contact staff about this course when I needed to.



n=7
av.=4.3
dev.=1.1
ab.=3
cf=85.71%

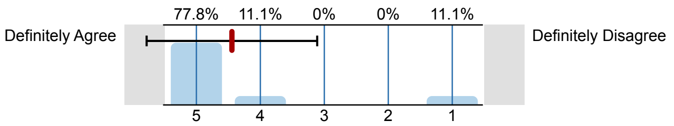
Please show the extent of your agreement by selecting the box that reflects your current view of your experience on this course to date:

3.7) 2.6 The criteria used in marking have been clear in advance.



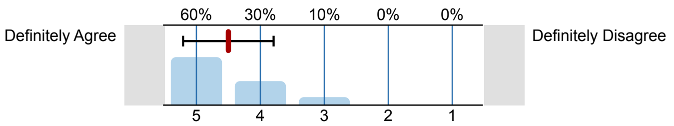
n=10
av.=3.4
dev.=1.3
cf=60.00%

3.8) 2.7 Marking and assessment has been fair.



n=9
av.=4.4
dev.=1.3
ab.=1
cf=88.89%

3.9) 2.8 The feedback I received has helped my learning and performance on the course.



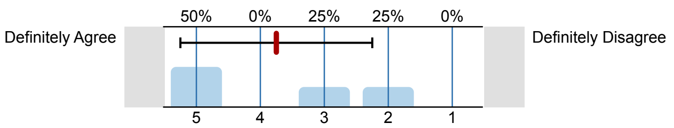
n=10
av.=4.5
dev.=0.7
cf=90.00%

3.10) 2.9 Do you have a reading list for this course?

Yes 0%
No 100%

n=10

3.12) 2.9c I have been able to access all my essential readings for this course.



n=4
av.=3.8
dev.=1.5
ab.=6
cf=50.00%

3.13) 2.9d I have been able to access all my further readings for this course.

	5	4	3	2	1		
Definitely Agree	50%	0%	25%	25%	0%	Definitely Disagree	n=4 av.=3.8 dev.=1.5 ab.=6 cf=50.00%

3.14) 2.10 I found course materials and activities accessed through Moodle useful for my studies on this course.

	5	4	3	2	1		
Definitely Agree	66.7%	33.3%	0%	0%	0%	Definitely Disagree	n=9 av.=4.7 dev.=0.5 ab.=1 cf=100.00%

3.15) 2.11 The course material provided was useful for my studies and learning.

	5	4	3	2	1		
Definitely Agree	66.7%	33.3%	0%	0%	0%	Definitely Disagree	n=9 av.=4.7 dev.=0.5 ab.=1 cf=100.00%

3.16) 2.12 Do you have lectures for this course?

Yes	100%	n=10
No	0%	

3.17) 2.12b How are lectures delivered on this course:

face-to-face on-campus lectures	0%	n=10
live online lectures (e.g. via Zoom)	100%	
pre-recorded lectures	0%	
pre-recorded micro/short/mini lectures	0%	
pre-recorded lectures plus live Q&A	0%	
some combination of the above	0%	

3.18) 2.12c I am satisfied with the integration of classes/ seminars with lectures on this course.

	5	4	3	2	1		
Definitely Agree	70%	30%	0%	0%	0%	Definitely Disagree	n=10 av.=4.7 dev.=0.5 cf=100.00%

3.19) 2.13 Have you experienced on campus classroom teaching where some of the students are not physically in the classroom but participate via Zoom ('hybrid' classes)

Yes	0%	n=10
No	100%	

3.25) 2.14 Overall, I am satisfied with my experience on this course.

	5	4	3	2	1		
Definitely Agree	50%	20%	10%	10%	10%	Definitely Disagree	n=10 av.=3.9 dev.=1.4 cf=70.00%

3.26) 2.15 Would you recommend this course to other students?

Yes	70%	n=10
Maybe	10%	
No	20%	

3.27) 2.16 Please comment below on aspects of this course you think were particularly good.

- Not much.
- Relevance of the content and the guest lecturers in lectures.

3.28) 2.16b Please comment below on aspects of this course you think could be improved.

- Course is arguably too fast paced for normal students and doesn't emphasize crucial elements of micro. The course doesn't teach students how to write out their own models as would be expected at a university such as harvard or mit. This course could most certainly use more math in the sense of modeling economic phenomenon at least at the level of the Ec 1P1 course. It is completely insane that as a math student you have less math in the Econ course than the Econ students do when you're in more math modules. Further, the course felt sort of rushed with a week spent on producer theory and consumer theory feeling insufficient to fully cover the topic. The game theory part was also not nearly as interesting as the Yale course that's online nor was it explained as well. The marking criteria also should be clearer. It should be clear what each point is given for and more significantly it should be prompted for in the question paper. There's no reason you should lose points for things you know. In the future, this course or the course next year at a minimum should embrace modeling projects to allow students to be trained in how to write out models for economic research, which can then be followed by metrics so they know how to do these things empirically. An example to base this or the second year micro course off of in the future would be Harvard's Ec1011a or Berkeley's Ec101a.

- Needs to be more clear what the mark scheme is for exams.
  Fact that there is limited number of past papers to practice with.
  Limited number of exam resources

4. Your Information

4.1) 3.1 Which of the reasons given below describe why you are taking the course? *(Please select all that apply)*

It is compulsory for my degree programme	90%	n=10
I chose the course as an option for my degree programme	10%	
I am interested in the subject matter	20%	
It was recommended to me by other students	10%	
It was recommended to me by an academic	0%	
Other	0%	

4.2) 3.1b Was this your 1st, 2nd, 3rd or other choice?

1st choice	100%	n=1
2nd choice	0%	
3rd choice	0%	
Other choice	0%	

4.3) 3.1c In relation to what you wanted to study, how important was choosing this course to you?

Very Important	5	4	3	2	1	Not at all Important
	100%	0%	0%	0%	0%	

n=1
av.=5
dev.=0
cf=100.00%

4.4) 3.2 How many hours of independent study do you put into this course each week outside of lectures, classes, and seminars?

More than 10 hours	20%	n=10
6-10 hours	30%	
2-5 hours	40%	
Less than 2 hours	10%	
None	0%	
N/A	0%	

4.6) 3.4 Do you have any Teaching and Learning Adjustments related to a declared disability?

Yes	0%	n=10
No	100%	

4.9) 3.5 Overall, I have not had problems with digital access to Moodle or other technologies throughout the term.

Definitely Agree	5	4	3	2	1	Definitely Disagree
	60%	20%	0%	20%	0%	

n=10
av.=4.2
dev.=1.2
cf=80.00%

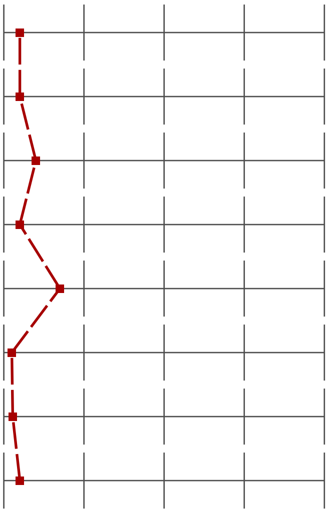
Profile

Subunit: EC - Economics
Name of the instructor: Ghassane Benmir
Name of the course: (Name of the survey) EC1A3.A Microeconomics I - Group 9

Values used in the profile line: Mean

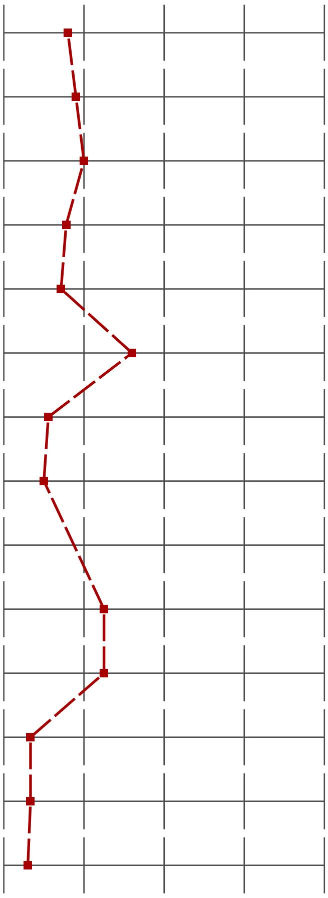
1. Class/Seminar Teacher Evaluation

1.2)	1.1 The teacher communicated ideas and concepts effectively.	Definitely Agree	Definitely Disagree	n=10	av.=4.8
1.3)	1.2 The teacher has improved my understanding of the course content.	Definitely Agree	Definitely Disagree	n=10	av.=4.8
1.4)	1.3 The teacher has made the subject interesting.	Definitely Agree	Definitely Disagree	n=10	av.=4.6
1.6)	1.4b The teacher is good at involving members of the class/seminar.	Definitely Agree	Definitely Disagree	n=10	av.=4.8
1.8)	1.5b Feedback on my work has been timely (typically 3-4 weeks after submission).	Definitely Agree	Definitely Disagree	n=10	av.=4.3
1.9)	1.5c I have received helpful comments on my work.	Definitely Agree	Definitely Disagree	n=10	av.=4.9
1.10)	1.5d I was able to seek further clarification on feedback from the teacher where needed.	Definitely Agree	Definitely Disagree	n=9	av.=4.9
1.11)	1.6 Overall, I am satisfied with the class/seminar teaching by this teacher on this course.	Definitely Agree	Definitely Disagree	n=10	av.=4.8



3. Course Evaluation

3.1)	2.1 This course has challenged me to achieve my best work.	Definitely Agree	Definitely Disagree	n=10	av.=4.2
3.2)	2.2 This course is intellectually stimulating.	Definitely Agree	Definitely Disagree	n=10	av.=4.1
3.3)	2.3 I have received sufficient advice and guidance in relation to this course to date.	Definitely Agree	Definitely Disagree	n=10	av.=4.0
3.4)	2.4 I am satisfied with the amount of contact time with teachers for this course.	Definitely Agree	Definitely Disagree	n=9	av.=4.2
3.6)	2.5 I have been able to contact staff about this course when I needed to.	Definitely Agree	Definitely Disagree	n=7	av.=4.3
3.7)	2.6 The criteria used in marking have been clear in advance.	Definitely Agree	Definitely Disagree	n=10	av.=3.4
3.8)	2.7 Marking and assessment has been fair.	Definitely Agree	Definitely Disagree	n=9	av.=4.4
3.9)	2.8 The feedback I received has helped my learning and performance on the course.	Definitely Agree	Definitely Disagree	n=10	av.=4.5
3.11)	2.9b The reading list(s) was useful for my learning. (*)	Definitely Agree	Definitely Disagree		
3.12)	2.9c I have been able to access all my essential readings for this course.	Definitely Agree	Definitely Disagree	n=4	av.=3.8
3.13)	2.9d I have been able to access all my further readings for this course.	Definitely Agree	Definitely Disagree	n=4	av.=3.8
3.14)	2.10 I found course materials and activities accessed through Moodle useful for my studies on this course.	Definitely Agree	Definitely Disagree	n=9	av.=4.7
3.15)	2.11 The course material provided was useful for my studies and learning.	Definitely Agree	Definitely Disagree	n=9	av.=4.7
3.18)	2.12c I am satisfied with the integration of classes/ seminars with lectures on this course.	Definitely Agree	Definitely Disagree	n=10	av.=4.7



3.21)	2.13c Overall, I am satisfied with the teaching in these ‘hybrid’ classes/seminars. (*)	Definitely Agree	Definitely Disagree		
3.22)	2.13d I have been able to participate actively in these classes/seminars. (*)	Definitely Agree	Definitely Disagree		
3.23)	2.13e Thinking about the technologies used (audio, visual), these classes/seminars have worked well. (*)	Definitely Agree	Definitely Disagree		
3.25)	2.14 Overall, I am satisfied with my experience on this course.	Definitely Agree	Definitely Disagree	n=10	av.=3.9

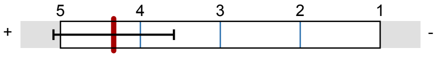
4. Your Information

4.3)	3.1c In relation to what you wanted to study, how important was choosing this course to you?	Very Important	Not at all Important	n=1	av.=5.0
4.5)	3.3 Please rate your own contribution to classes/ seminars. (*)	Very Good	Poor		
4.9)	3.5 Overall, I have not had problems with digital access to Moodle or other technologies throughout the term.	Definitely Agree	Definitely Disagree	n=10	av.=4.2

Ghassane Benmir
EC1A3.A Microeconomics I - Group 10
No. of responses = 13

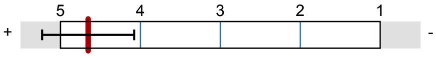
Overall indicators

Global Index



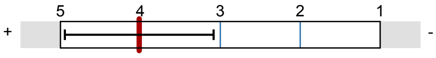
av.=4.3
dev.=0.8

Class/Seminar Teacher Evaluation (Scale width: 5)



av.=4.7
dev.=0.6

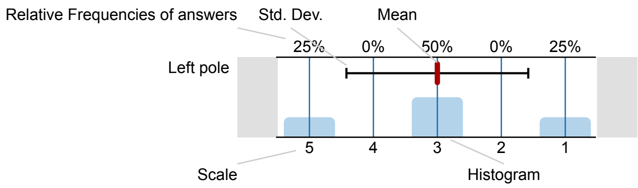
Course Evaluation (Scale width: 5)



av.=4
dev.=0.9

Legend

Question text



n=No. of responses
av.=Mean
dev.=Std. Dev.
ab.=Abstention
cf=Cumulative Frequency

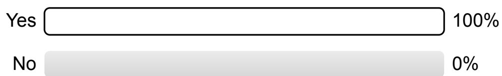
1. Class/Seminar Teacher Evaluation

This survey requests your feedback on two separate aspects of your learning experience, split into three sections. The first section asks for your views on your teacher's class/seminar teaching. The second section asks for your views on the course as a whole at this point in time. Finally, the third section asks for some information about you, to aid analysis.

We recognise that this term has been particularly challenging for everyone due to the wider public health situation, with disruption experienced by both students and teaching staff. The School is continually striving to deliver the best possible educational experience despite these challenges and your views about your learning experience at LSE are a valuable source of information about this. The results will be used to help improve the teaching and learning experience for you and your peers and to identify good practice.

The School assumes that your response is broadly positive if you 'mostly agree' or 'definitely agree' with a statement.

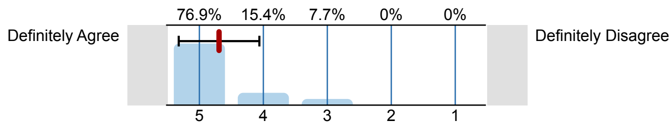
1.1) Do the answers you supply below relate to the teacher from whom you have received the majority of your class/seminar teaching this term? The teacher's name, course title and group number (where relevant) are provided in the invitation email you have received for the survey.



n=12

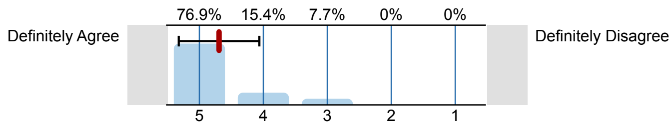
Please show the extent of your agreement by selecting the box that reflects your current view of your class/seminar teacher:

1.2) 1.1 The teacher communicated ideas and concepts effectively.



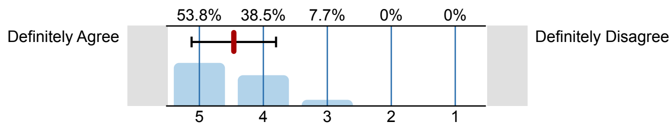
n=13
av.=4.7
dev.=0.6
cf=92.31%

1.3) 1.2 The teacher has improved my understanding of the course content.



n=13
av.=4.7
dev.=0.6
cf=92.31%

1.4) 1.3 The teacher has made the subject interesting.



n=13
av.=4.5
dev.=0.7
cf=92.31%

1.5) 1.4 Have you attended classes/seminars for this class/seminar:

on-campus	84.6%	n=13
online	0%	
both	15.4%	

1.6) 1.4b The teacher is good at involving members of the class/seminar.

Definitely Agree	5	4	3	2	1	Definitely Disagree
	61.5%	30.8%	7.7%	0%	0%	

n=13
av.=4.5
dev.=0.7
cf=92.31%

1.7) 1.5 Have you received feedback on your work from this teacher?

Yes	91.7%	n=12
No	8.3%	

Please show the extent of your agreement by selecting the box that reflects your current view of your class/seminar teacher:

1.8) 1.5b Feedback on my work has been timely (typically 3-4 weeks after submission).

Definitely Agree	5	4	3	2	1	Definitely Disagree
	63.6%	27.3%	0%	9.1%	0%	

n=11
av.=4.5
dev.=0.9
cf=90.91%

1.9) 1.5c I have received helpful comments on my work.

Definitely Agree	5	4	3	2	1	Definitely Disagree
	72.7%	27.3%	0%	0%	0%	

n=11
av.=4.7
dev.=0.5
cf=100.00%

1.10) 1.5d I was able to seek further clarification on feedback from the teacher where needed.

Definitely Agree	5	4	3	2	1	Definitely Disagree
	100%	0%	0%	0%	0%	

n=11
av.=5
dev.=0
cf=100.00%

Please show the extent of your agreement by selecting the box that reflects your current view of your class/seminar teacher:

1.11) 1.6 Overall, I am satisfied with the class/seminar teaching by this teacher on this course.

Definitely Agree	5	4	3	2	1	Definitely Disagree
	76.9%	15.4%	7.7%	0%	0%	

n=13
av.=4.7
dev.=0.6
cf=92.31%

1.12) 1.7 Please comment below on aspects of this teacher's class/seminar teaching you think were particularly helpful.

- Able to give good real-life examples to help us understand concepts
- Feedback / Exam Technique
- Going through the MCQ's and Problem Sets really helps me understand what mistakes i made
- Good at explaining and making difficult concepts easier to understand.
  Also quite interesting.
- Made us understand how to do problems effectively
- The classes were interested. By his communication it is evident he worked as a consultant for some time, his speech is really structured and eloquent. Would love to have him as a teacher for the next term too.
- going through problem sets and mcq questions every week and how to approach the task too

1.13) 1.7b Please comment below on aspects of this teacher's class/seminar teaching you think could be improved.

- Maybe went to fast (but we did have a lot of content to get through)
- Not much
- Sometimes maybe a bit fast when doing solutions
- go through mid week task too

2. Thank you - Part 1 Complete

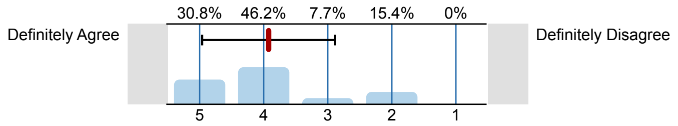
Thank you for completing the teacher evaluation of the class/seminar survey.

The next part of the survey asks for your views on the course as a whole. It is not restricted to this particular teacher, but to the entire experience you have had on this course to date.

3. Course Evaluation

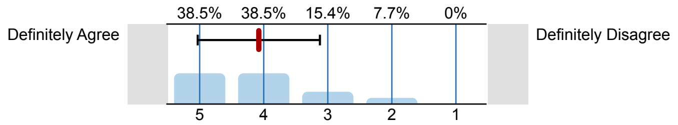
Please show the extent of your agreement by selecting the box that reflects your current view of your experience on this course to date:

3.1) 2.1 This course has challenged me to achieve my best work.



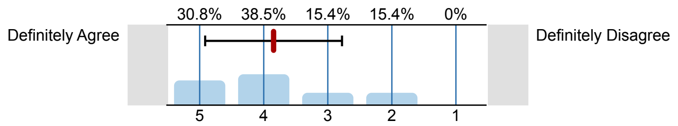
n=13
av.=3.9
dev.=1
cf=76.92%

3.2) 2.2 This course is intellectually stimulating.



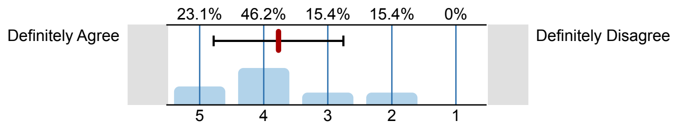
n=13
av.=4.1
dev.=1
cf=76.92%

3.3) 2.3 I have received sufficient advice and guidance in relation to this course to date.



n=13
av.=3.8
dev.=1.1
cf=69.23%

3.4) 2.4 I am satisfied with the amount of contact time with teachers for this course.

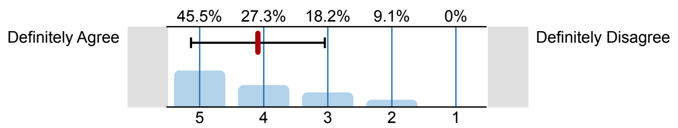


n=13
av.=3.8
dev.=1
cf=69.23%

3.5) 2.4b Please comment below about why contact time with teachers has been less than satisfactory.

- I would prefer two classes a week for this level of pace

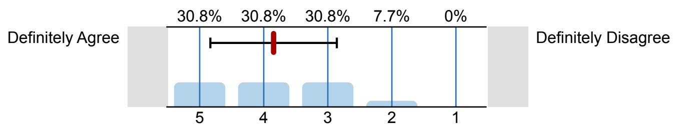
3.6) 2.5 I have been able to contact staff about this course when I needed to.



n=11
av.=4.1
dev.=1
ab.=2
cf=72.73%

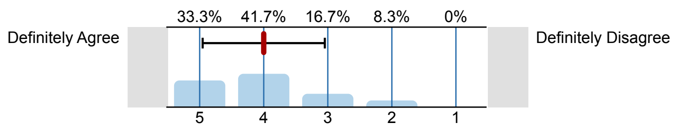
Please show the extent of your agreement by selecting the box that reflects your current view of your experience on this course to date:

3.7) 2.6 The criteria used in marking have been clear in advance.



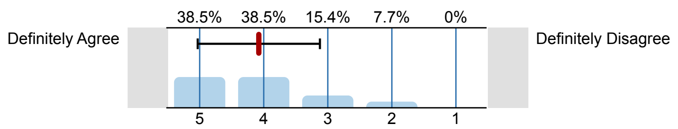
n=13
av.=3.8
dev.=1
cf=61.54%

3.8) 2.7 Marking and assessment has been fair.



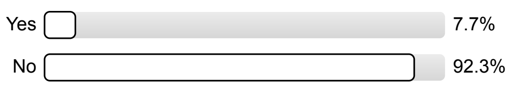
n=12
av.=4
dev.=1
ab.=1
cf=75.00%

3.9) 2.8 The feedback I received has helped my learning and performance on the course.



n=13
av.=4.1
dev.=1
cf=76.92%

3.10) 2.9 Do you have a reading list for this course?



n=13

3.11) 2.9b The reading list(s) was useful for my learning.

Definitely Agree | 5: 0% | 4: 0% | 3: 100% | 2: 0% | 1: 0% | Definitely Disagree

n=1
av.=3
dev.=0
cf=0.00%

3.12) 2.9c I have been able to access all my essential readings for this course.

Definitely Agree | 5: 28.6% | 4: 14.3% | 3: 28.6% | 2: 28.6% | 1: 0% | Definitely Disagree

n=7
av.=3.4
dev.=1.3
ab.=6
cf=42.86%

3.13) 2.9d I have been able to access all my further readings for this course.

Definitely Agree | 5: 33.3% | 4: 33.3% | 3: 16.7% | 2: 16.7% | 1: 0% | Definitely Disagree

n=6
av.=3.8
dev.=1.2
ab.=7
cf=66.67%

3.14) 2.10 I found course materials and activities accessed through Moodle useful for my studies on this course.

Definitely Agree | 5: 58.3% | 4: 25% | 3: 8.3% | 2: 8.3% | 1: 0% | Definitely Disagree

n=12
av.=4.3
dev.=1
ab.=1
cf=83.33%

3.15) 2.11 The course material provided was useful for my studies and learning.

Definitely Agree | 5: 58.3% | 4: 16.7% | 3: 16.7% | 2: 8.3% | 1: 0% | Definitely Disagree

n=12
av.=4.3
dev.=1.1
ab.=1
cf=75.00%

3.16) 2.12 Do you have lectures for this course?

Yes	100%	n=13
No	0%	

3.17) 2.12b How are lectures delivered on this course:

face-to-face on-campus lectures	0%	n=13
live online lectures (e.g. via Zoom)	84.6%	
pre-recorded lectures	0%	
pre-recorded micro/short/mini lectures	0%	
pre-recorded lectures plus live Q&A	0%	
some combination of the above	15.4%	

3.18) 2.12c I am satisfied with the integration of classes/ seminars with lectures on this course.

Definitely Agree | 5: 46.2% | 4: 30.8% | 3: 23.1% | 2: 0% | 1: 0% | Definitely Disagree

n=13
av.=4.2
dev.=0.8
cf=76.92%

3.19) 2.13 Have you experienced on campus classroom teaching where some of the students are not physically in the classroom but participate via Zoom (‘hybrid’ classes)

Yes	0%	n=11
No	100%	

3.25) 2.14 Overall, I am satisfied with my experience on this course.

Definitely Agree | 5: 46.2% | 4: 30.8% | 3: 7.7% | 2: 15.4% | 1: 0% | Definitely Disagree

n=13
av.=4.1
dev.=1.1
cf=76.92%

3.26) 2.15 Would you recommend this course to other students?

Yes	53.8%	n=13
Maybe	30.8%	
No	15.4%	

3.27) 2.16 Please comment below on aspects of this course you think were particularly good.

- Application to real life was interesting, lecturer was engaging.
- Good examples make the class fun
- The structure of the exams
- cool to understand microeconmics

3.28) 2.16b Please comment below on aspects of this course you think could be improved.

- Mid-week is sometimes not related to the topic of course
- Provide lecture notes
- Too hard, and too fast with too little time to properly cover the content so it is hard to understand how to do problems.
- We need lecture notes!
- rather different to what we did in a level

4. Your Information

4.1) 3.1 Which of the reasons given below describe why you are taking the course? *(Please select all that apply)*

It is compulsory for my degree programme	100%	n=13
I chose the course as an option for my degree programme	0%	
I am interested in the subject matter	0%	
It was recommended to me by other students	0%	
It was recommended to me by an academic	0%	
Other	0%	

4.4) 3.2 How many hours of independent study do you put into this course each week outside of lectures, classes, and seminars?

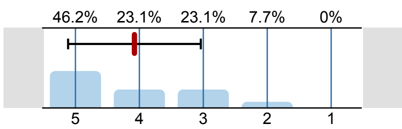
More than 10 hours	0%	n=13
6-10 hours	38.5%	
2-5 hours	38.5%	
Less than 2 hours	15.4%	
None	7.7%	
N/A	0%	

4.6) 3.4 Do you have any Teaching and Learning Adjustments related to a declared disability?

Yes	0%	n=13
No	100%	

4.9) 3.5 Overall, I have not had problems with digital access to Moodle or other technologies throughout the term.

Definitely Agree



Definitely Disagree

n=13
av.=4.1
dev.=1
cf=69.23%

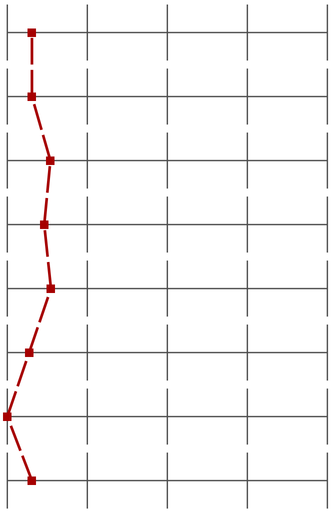
Profile

Subunit: EC - Economics
Name of the instructor: Ghassane Benmir
Name of the course: (Name of the survey) EC1A3.A Microeconomics I - Group 10

Values used in the profile line: Mean

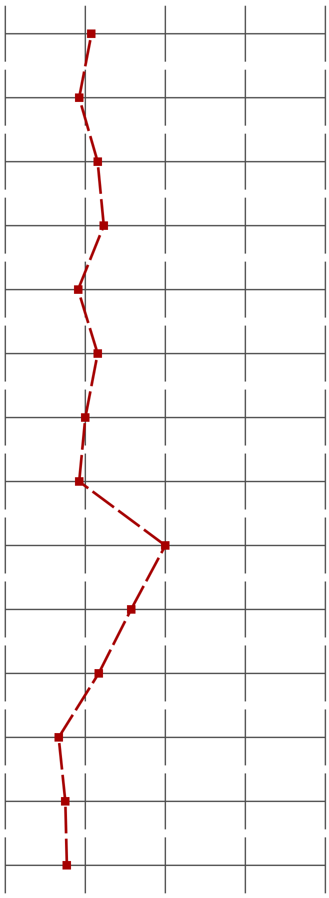
1. Class/Seminar Teacher Evaluation

1.2)	1.1 The teacher communicated ideas and concepts effectively.	Definitely Agree	Definitely Disagree	n=13	av.=4.7
1.3)	1.2 The teacher has improved my understanding of the course content.	Definitely Agree	Definitely Disagree	n=13	av.=4.7
1.4)	1.3 The teacher has made the subject interesting.	Definitely Agree	Definitely Disagree	n=13	av.=4.5
1.6)	1.4b The teacher is good at involving members of the class/seminar.	Definitely Agree	Definitely Disagree	n=13	av.=4.5
1.8)	1.5b Feedback on my work has been timely (typically 3-4 weeks after submission).	Definitely Agree	Definitely Disagree	n=11	av.=4.5
1.9)	1.5c I have received helpful comments on my work.	Definitely Agree	Definitely Disagree	n=11	av.=4.7
1.10)	1.5d I was able to seek further clarification on feedback from the teacher where needed.	Definitely Agree	Definitely Disagree	n=11	av.=5.0
1.11)	1.6 Overall, I am satisfied with the class/seminar teaching by this teacher on this course.	Definitely Agree	Definitely Disagree	n=13	av.=4.7



3. Course Evaluation

3.1)	2.1 This course has challenged me to achieve my best work.	Definitely Agree	Definitely Disagree	n=13	av.=3.9
3.2)	2.2 This course is intellectually stimulating.	Definitely Agree	Definitely Disagree	n=13	av.=4.1
3.3)	2.3 I have received sufficient advice and guidance in relation to this course to date.	Definitely Agree	Definitely Disagree	n=13	av.=3.8
3.4)	2.4 I am satisfied with the amount of contact time with teachers for this course.	Definitely Agree	Definitely Disagree	n=13	av.=3.8
3.6)	2.5 I have been able to contact staff about this course when I needed to.	Definitely Agree	Definitely Disagree	n=11	av.=4.1
3.7)	2.6 The criteria used in marking have been clear in advance.	Definitely Agree	Definitely Disagree	n=13	av.=3.8
3.8)	2.7 Marking and assessment has been fair.	Definitely Agree	Definitely Disagree	n=12	av.=4.0
3.9)	2.8 The feedback I received has helped my learning and performance on the course.	Definitely Agree	Definitely Disagree	n=13	av.=4.1
3.11)	2.9b The reading list(s) was useful for my learning.	Definitely Agree	Definitely Disagree	n=1	av.=3.0
3.12)	2.9c I have been able to access all my essential readings for this course.	Definitely Agree	Definitely Disagree	n=7	av.=3.4
3.13)	2.9d I have been able to access all my further readings for this course.	Definitely Agree	Definitely Disagree	n=6	av.=3.8
3.14)	2.10 I found course materials and activities accessed through Moodle useful for my studies on this course.	Definitely Agree	Definitely Disagree	n=12	av.=4.3
3.15)	2.11 The course material provided was useful for my studies and learning.	Definitely Agree	Definitely Disagree	n=12	av.=4.3
3.18)	2.12c I am satisfied with the integration of classes/ seminars with lectures on this course.	Definitely Agree	Definitely Disagree	n=13	av.=4.2



3.21)	2.13c Overall, I am satisfied with the teaching in these ‘hybrid’ classes/seminars. (*)	Definitely Agree		Definitely Disagree		
3.22)	2.13d I have been able to participate actively in these classes/seminars. (*)	Definitely Agree		Definitely Disagree		
3.23)	2.13e Thinking about the technologies used (audio, visual), these classes/seminars have worked well. (*)	Definitely Agree		Definitely Disagree		
3.25)	2.14 Overall, I am satisfied with my experience on this course.	Definitely Agree		Definitely Disagree	n=13	av.=4.1

4. Your Information

4.3)	3.1c In relation to what you wanted to study, how important was choosing this course to you? (*)	Very Important		Not at all Important		
4.5)	3.3 Please rate your own contribution to classes/seminars. (*)	Very Good		Poor		
4.9)	3.5 Overall, I have not had problems with digital access to Moodle or other technologies throughout the term.	Definitely Agree		Definitely Disagree	n=13	av.=4.1

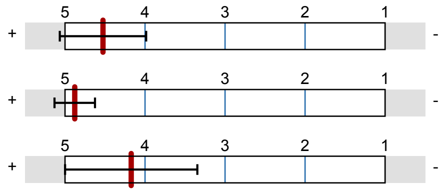
Ghassane Benmir
EC1A3.A Microeconomics I - Group 11
No. of responses = 10

Overall indicators

Global Index

Class/Seminar Teacher Evaluation (Scale width: 5)

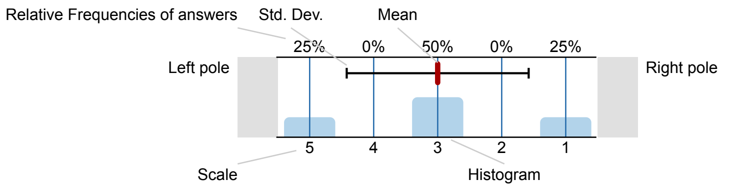
Course Evaluation (Scale width: 5)



Global Index: av.=4.5 dev.=0.5
Class/Seminar Teacher Evaluation: av.=4.9 dev.=0.3
Course Evaluation: av.=4.2 dev.=0.8

Legend

Question text



n=No. of responses
av.=Mean
dev.=Std. Dev.
ab.=Abstention
cf=Cumulative Frequency

1. Class/Seminar Teacher Evaluation

This survey requests your feedback on two separate aspects of your learning experience, split into three sections. The first section asks for your views on your teacher's class/seminar teaching. The second section asks for your views on the course as a whole at this point in time. Finally, the third section asks for some information about you, to aid analysis.

We recognise that this term has been particularly challenging for everyone due to the wider public health situation, with disruption experienced by both students and teaching staff. The School is continually striving to deliver the best possible educational experience despite these challenges and your views about your learning experience at LSE are a valuable source of information about this. The results will be used to help improve the teaching and learning experience for you and your peers and to identify good practice.

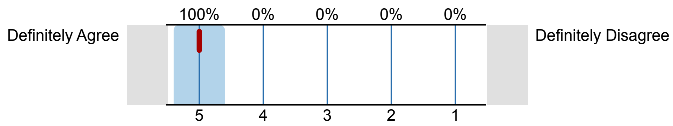
The School assumes that your response is broadly positive if you 'mostly agree' or 'definitely agree' with a statement.

1.1) Do the answers you supply below relate to the teacher from whom you have received the majority of your class/seminar teaching this term? The teacher's name, course title and group number (where relevant) are provided in the invitation email you have received for the survey.

Yes	100%	n=10
No	0%	

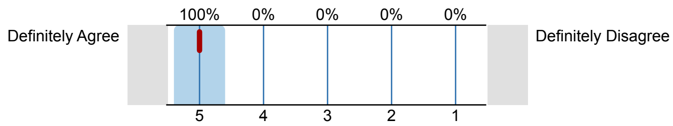
Please show the extent of your agreement by selecting the box that reflects your current view of your class/seminar teacher:

1.2) 1.1 The teacher communicated ideas and concepts effectively.



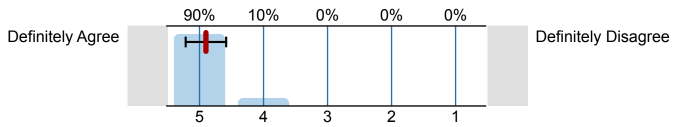
n=10
av.=5
dev.=0
cf=100.00%

1.3) 1.2 The teacher has improved my understanding of the course content.



n=10
av.=5
dev.=0
cf=100.00%

1.4) 1.3 The teacher has made the subject interesting.



n=10
av.=4.9
dev.=0.3
cf=100.00%

1.5) 1.4 Have you attended classes/seminars for this class/seminar:

on-campus	100%	n=10
online	0%	
both	0%	

1.6) 1.4b The teacher is good at involving members of the class/seminar.

	5	4	3	2	1		
Definitely Agree	70%	30%	0%	0%	0%	Definitely Disagree	n=10 av.=4.7 dev.=0.5 cf=100.00%

1.7) 1.5 Have you received feedback on your work from this teacher?

Yes	80%	n=10
No	20%	

Please show the extent of your agreement by selecting the box that reflects your current view of your class/seminar teacher:

1.8) 1.5b Feedback on my work has been timely (typically 3-4 weeks after submission).

	5	4	3	2	1		
Definitely Agree	62.5%	37.5%	0%	0%	0%	Definitely Disagree	n=8 av.=4.6 dev.=0.5 cf=100.00%

1.9) 1.5c I have received helpful comments on my work.

	5	4	3	2	1		
Definitely Agree	87.5%	12.5%	0%	0%	0%	Definitely Disagree	n=8 av.=4.9 dev.=0.4 cf=100.00%

1.10) 1.5d I was able to seek further clarification on feedback from the teacher where needed.

	5	4	3	2	1		
Definitely Agree	87.5%	12.5%	0%	0%	0%	Definitely Disagree	n=8 av.=4.9 dev.=0.4 cf=100.00%

Please show the extent of your agreement by selecting the box that reflects your current view of your class/seminar teacher:

1.11) 1.6 Overall, I am satisfied with the class/seminar teaching by this teacher on this course.

	5	4	3	2	1		
Definitely Agree	100%	0%	0%	0%	0%	Definitely Disagree	n=10 av.=5 dev.=0 cf=100.00%

1.12) 1.7 Please comment below on aspects of this teacher's class/seminar teaching you think were particularly helpful.

- -
- - answers all questions
- I like how he goes over both the MCQs and problem sets, making sure everyone understands before he moves on
- Makes the class interesting by involving real life examples
  Very clear explanation of problem sets and midweek tasks
- Summary slides
- Weekly summary
  Going through the steps of completing the problem set
- explaining the concept one by one
- has a clear structure to the class, clears up confusing concepts, focuses on exam technique, involves the class a lot

1.13) 1.7b Please comment below on aspects of this teacher's class/seminar teaching you think could be improved.

- -
- -
- N/A
- N/A

- Question time at the end maybe?
- nothing

2. Thank you - Part 1 Complete

Thank you for completing the teacher evaluation of the class/seminar survey.

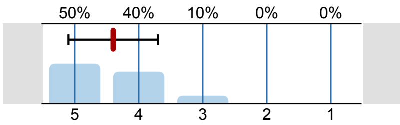
The next part of the survey asks for your views on the course as a whole. It is not restricted to this particular teacher, but to the entire experience you have had on this course to date.

3. Course Evaluation

Please show the extent of your agreement by selecting the box that reflects your current view of your experience on this course to date:

3.1) 2.1 This course has challenged me to achieve my best work.

Definitely Agree

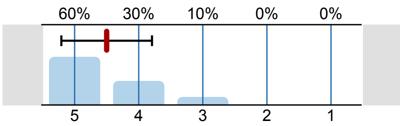


Definitely Disagree

n=10
av.=4.4
dev.=0.7
cf=90.00%

3.2) 2.2 This course is intellectually stimulating.

Definitely Agree

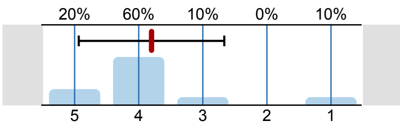


Definitely Disagree

n=10
av.=4.5
dev.=0.7
cf=90.00%

3.3) 2.3 I have received sufficient advice and guidance in relation to this course to date.

Definitely Agree

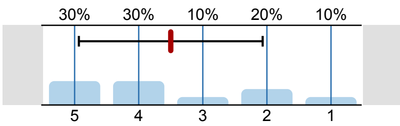


Definitely Disagree

n=10
av.=3.8
dev.=1.1
cf=80.00%

3.4) 2.4 I am satisfied with the amount of contact time with teachers for this course.

Definitely Agree



Definitely Disagree

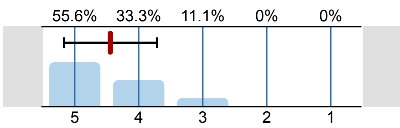
n=10
av.=3.5
dev.=1.4
cf=60.00%

3.5) 2.4b Please comment below about why contact time with teachers has been less than satisfactory.

- Short contact time
- class is short
- the lectures do not provide enough time for the lecturer to go over exam style problems and the more quantitative aspects of the course- so we end up confused when looking at the problem sets

3.6) 2.5 I have been able to contact staff about this course when I needed to.

Definitely Agree



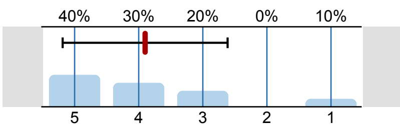
Definitely Disagree

n=9
av.=4.4
dev.=0.7
ab.=1
cf=88.89%

Please show the extent of your agreement by selecting the box that reflects your current view of your experience on this course to date:

3.7) 2.6 The criteria used in marking have been clear in advance.

Definitely Agree

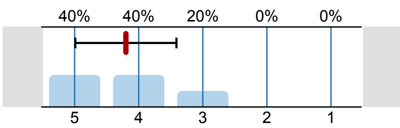


Definitely Disagree

n=10
av.=3.9
dev.=1.3
cf=70.00%

3.8) 2.7 Marking and assessment has been fair.

Definitely Agree



Definitely Disagree

n=10
av.=4.2
dev.=0.8
cf=80.00%

3.9) 2.8 The feedback I received has helped my learning and performance on the course.

Definitely Agree	5	4	3	2	1	Definitely Disagree	
	70%	20%	0%	0%	10%		n=10 av.=4.4 dev.=1.3 cf=90.00%

3.10) 2.9 Do you have a reading list for this course?

Yes	10%	n=10
No	90%	

3.11) 2.9b The reading list(s) was useful for my learning.

Definitely Agree	5	4	3	2	1	Definitely Disagree	
	0%	100%	0%	0%	0%		n=1 av.=4 dev.=0 cf=100.00%

3.12) 2.9c I have been able to access all my essential readings for this course.

Definitely Agree	5	4	3	2	1	Definitely Disagree	
	50%	50%	0%	0%	0%		n=6 av.=4.5 dev.=0.5 ab.=4 cf=100.00%

3.13) 2.9d I have been able to access all my further readings for this course.

Definitely Agree	5	4	3	2	1	Definitely Disagree	
	66.7%	16.7%	16.7%	0%	0%		n=6 av.=4.5 dev.=0.8 ab.=4 cf=83.33%

3.14) 2.10 I found course materials and activities accessed through Moodle useful for my studies on this course.

Definitely Agree	5	4	3	2	1	Definitely Disagree	
	30%	60%	0%	10%	0%		n=10 av.=4.1 dev.=0.9 cf=90.00%

3.15) 2.11 The course material provided was useful for my studies and learning.

Definitely Agree	5	4	3	2	1	Definitely Disagree	
	30%	70%	0%	0%	0%		n=10 av.=4.3 dev.=0.5 cf=100.00%

3.16) 2.12 Do you have lectures for this course?

Yes	90%	n=10
No	10%	

3.17) 2.12b How are lectures delivered on this course:

face-to-face on-campus lectures	0%	n=9
live online lectures (e.g. via Zoom)	77.8%	
pre-recorded lectures	0%	
pre-recorded micro/short/mini lectures	0%	
pre-recorded lectures plus live Q&A	11.1%	
some combination of the above	11.1%	

3.18) 2.12c I am satisfied with the integration of classes/ seminars with lectures on this course.

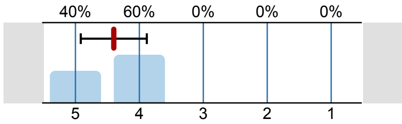
Definitely Agree	5	4	3	2	1	Definitely Disagree	
	22.2%	66.7%	11.1%	0%	0%		n=9 av.=4.1 dev.=0.6 cf=88.89%

3.19) 2.13 Have you experienced on campus classroom teaching where some of the students are not physically in the classroom but participate via Zoom ('hybrid' classes)

Yes	0%	n=10
No	100%	

3.25) 2.14 Overall, I am satisfied with my experience on this course.

Definitely Agree



Definitely Disagree

n=10
av.=4.4
dev.=0.5
cf=100.00%

3.26) 2.15 Would you recommend this course to other students?

Yes	60%	n=10
Maybe	40%	
No	0%	

3.27) 2.16 Please comment below on aspects of this course you think were particularly good.

- -
- Application and it's challenging
- Challenging and precise
- Combination of qualitative and quantitative aspects of economics
  Trains you to apply abstract theories to real life scenarios
- It's interesting how it links to real life
- interesting concepts and real world applications

3.28) 2.16b Please comment below on aspects of this course you think could be improved.

- -
- Less content
- More exam-style practice
- More explanations on concepts for people who didn't study economics at A-Levels
- Often times the difficulty of problem sets are much higher than the problems explained during lectures, lectures sometimes seems over simplified
- teaching doesn't have a focus on exam

4. Your Information

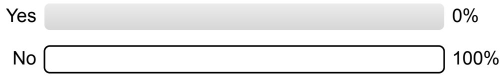
4.1) 3.1 Which of the reasons given below describe why you are taking the course? *(Please select all that apply)*

It is compulsory for my degree programme	100%	n=10
I chose the course as an option for my degree programme	0%	
I am interested in the subject matter	10%	
It was recommended to me by other students	0%	
It was recommended to me by an academic	0%	
Other	0%	

4.4) 3.2 How many hours of independent study do you put into this course each week outside of lectures, classes, and seminars?

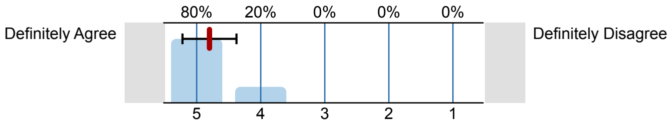
More than 10 hours	0%	n=10
6-10 hours	30%	
2-5 hours	60%	
Less than 2 hours	10%	
None	0%	
N/A	0%	

4.6) 3.4 Do you have any Teaching and Learning Adjustments related to a declared disability?



n=10

4.9) 3.5 Overall, I have not had problems with digital access to Moodle or other technologies throughout the term.



n=10
av.=4.8
dev.=0.4
cf=100.00%

Profile

Subunit:	EC - Economics
Name of the instructor:	Ghassane Benmir
Name of the course: (Name of the survey)	EC1A3.A Microeconomics I - Group 11

Values used in the profile line: Mean

1. Class/Seminar Teacher Evaluation

1.2)	1.1 The teacher communicated ideas and concepts effectively.	Definitely Agree — Definitely Disagree	n=10	av.=5.0
1.3)	1.2 The teacher has improved my understanding of the course content.	Definitely Agree — Definitely Disagree	n=10	av.=5.0
1.4)	1.3 The teacher has made the subject interesting.	Definitely Agree — Definitely Disagree	n=10	av.=4.9
1.6)	1.4b The teacher is good at involving members of the class/seminar.	Definitely Agree — Definitely Disagree	n=10	av.=4.7
1.8)	1.5b Feedback on my work has been timely (typically 3-4 weeks after submission).	Definitely Agree — Definitely Disagree	n=8	av.=4.6
1.9)	1.5c I have received helpful comments on my work.	Definitely Agree — Definitely Disagree	n=8	av.=4.9
1.10)	1.5d I was able to seek further clarification on feedback from the teacher where needed.	Definitely Agree — Definitely Disagree	n=8	av.=4.9
1.11)	1.6 Overall, I am satisfied with the class/seminar teaching by this teacher on this course.	Definitely Agree — Definitely Disagree	n=10	av.=5.0

3. Course Evaluation

3.1)	2.1 This course has challenged me to achieve my best work.	Definitely Agree — Definitely Disagree	n=10	av.=4.4
3.2)	2.2 This course is intellectually stimulating.	Definitely Agree — Definitely Disagree	n=10	av.=4.5
3.3)	2.3 I have received sufficient advice and guidance in relation to this course to date.	Definitely Agree — Definitely Disagree	n=10	av.=3.8
3.4)	2.4 I am satisfied with the amount of contact time with teachers for this course.	Definitely Agree — Definitely Disagree	n=10	av.=3.5
3.6)	2.5 I have been able to contact staff about this course when I needed to.	Definitely Agree — Definitely Disagree	n=9	av.=4.4
3.7)	2.6 The criteria used in marking have been clear in advance.	Definitely Agree — Definitely Disagree	n=10	av.=3.9
3.8)	2.7 Marking and assessment has been fair.	Definitely Agree — Definitely Disagree	n=10	av.=4.2
3.9)	2.8 The feedback I received has helped my learning and performance on the course.	Definitely Agree — Definitely Disagree	n=10	av.=4.4
3.11)	2.9b The reading list(s) was useful for my learning.	Definitely Agree — Definitely Disagree	n=1	av.=4.0
3.12)	2.9c I have been able to access all my essential readings for this course.	Definitely Agree — Definitely Disagree	n=6	av.=4.5
3.13)	2.9d I have been able to access all my further readings for this course.	Definitely Agree — Definitely Disagree	n=6	av.=4.5
3.14)	2.10 I found course materials and activities accessed through Moodle useful for my studies on this course.	Definitely Agree — Definitely Disagree	n=10	av.=4.1
3.15)	2.11 The course material provided was useful for my studies and learning.	Definitely Agree — Definitely Disagree	n=10	av.=4.3
3.18)	2.12c I am satisfied with the integration of classes/ seminars with lectures on this course.	Definitely Agree — Definitely Disagree	n=9	av.=4.1

3.21) 2.13c Overall, I am satisfied with the teaching in these ‘hybrid’ classes/seminars. (*)	Definitely Agree	Definitely Disagree		
3.22) 2.13d I have been able to participate actively in these classes/seminars. (*)	Definitely Agree	Definitely Disagree		
3.23) 2.13e Thinking about the technologies used (audio, visual), these classes/seminars have worked well. (*)	Definitely Agree	Definitely Disagree		
3.25) 2.14 Overall, I am satisfied with my experience on this course.	Definitely Agree	Definitely Disagree	n=10	av.=4.4

4. Your Information

4.3) 3.1c In relation to what you wanted to study, how important was choosing this course to you? (*)	Very Important	Not at all Important		
4.5) 3.3 Please rate your own contribution to classes/ seminars. (*)	Very Good	Poor		
4.9) 3.5 Overall, I have not had problems with digital access to Moodle or other technologies throughout the term.	Definitely Agree	Definitely Disagree	n=10	av.=4.8

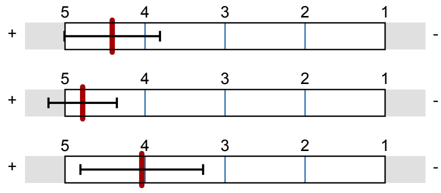
Ghassane Benmir
EC1A3.A Microeconomics I - Group 12
No. of responses = 9

Overall indicators

Global Index

Class/Seminar Teacher Evaluation (Scale width: 5)

Course Evaluation (Scale width: 5)



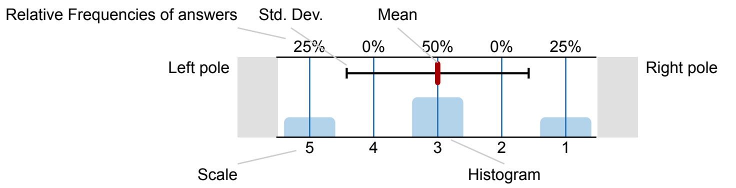
av.=4.4
dev.=0.6

av.=4.8
dev.=0.4

av.=4
dev.=0.8

Legend

Question text



n=No. of responses
av.=Mean
dev.=Std. Dev.
ab.=Abstention
cf=Cumulative Frequency

1. Class/Seminar Teacher Evaluation

This survey requests your feedback on two separate aspects of your learning experience, split into three sections. The first section asks for your views on your teacher's class/seminar teaching. The second section asks for your views on the course as a whole at this point in time. Finally, the third section asks for some information about you, to aid analysis.

We recognise that this term has been particularly challenging for everyone due to the wider public health situation, with disruption experienced by both students and teaching staff. The School is continually striving to deliver the best possible educational experience despite these challenges and your views about your learning experience at LSE are a valuable source of information about this. The results will be used to help improve the teaching and learning experience for you and your peers and to identify good practice.

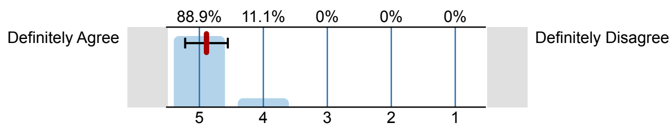
The School assumes that your response is broadly positive if you 'mostly agree' or 'definitely agree' with a statement.

1.1) Do the answers you supply below relate to the teacher from whom you have received the majority of your class/seminar teaching this term? The teacher's name, course title and group number (where relevant) are provided in the invitation email you have received for the survey.

Yes	100%	n=9
No	0%	

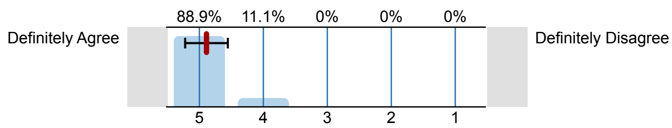
Please show the extent of your agreement by selecting the box that reflects your current view of your class/seminar teacher:

1.2) 1.1 The teacher communicated ideas and concepts effectively.



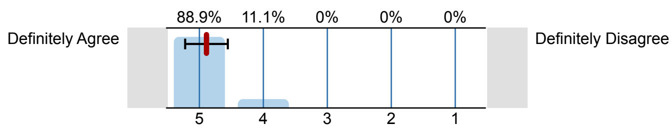
n=9
av.=4.9
dev.=0.3
cf=100.00%

1.3) 1.2 The teacher has improved my understanding of the course content.



n=9
av.=4.9
dev.=0.3
cf=100.00%

1.4) 1.3 The teacher has made the subject interesting.



n=9
av.=4.9
dev.=0.3
cf=100.00%

1.5) 1.4 Have you attended classes/seminars for this class/seminar:

on-campus	88.9%	n=9
online	0%	
both	11.1%	

1.6) 1.4b The teacher is good at involving members of the class/seminar.

	5	4	3	2	1		
Definitely Agree	55.6%	33.3%	11.1%	0%	0%	Definitely Disagree	n=9 av.=4.4 dev.=0.7 cf=88.89%

1.7) 1.5 Have you received feedback on your work from this teacher?

Yes	88.9%	n=9
No	11.1%	

Please show the extent of your agreement by selecting the box that reflects your current view of your class/seminar teacher:

1.8) 1.5b Feedback on my work has been timely (typically 3-4 weeks after submission).

	5	4	3	2	1		
Definitely Agree	62.5%	37.5%	0%	0%	0%	Definitely Disagree	n=8 av.=4.6 dev.=0.5 cf=100.00%

1.9) 1.5c I have received helpful comments on my work.

	5	4	3	2	1		
Definitely Agree	75%	25%	0%	0%	0%	Definitely Disagree	n=8 av.=4.8 dev.=0.5 cf=100.00%

1.10) 1.5d I was able to seek further clarification on feedback from the teacher where needed.

	5	4	3	2	1		
Definitely Agree	85.7%	14.3%	0%	0%	0%	Definitely Disagree	n=7 av.=4.9 dev.=0.4 ab.=1 cf=100.00%

Please show the extent of your agreement by selecting the box that reflects your current view of your class/seminar teacher:

1.11) 1.6 Overall, I am satisfied with the class/seminar teaching by this teacher on this course.

	5	4	3	2	1		
Definitely Agree	88.9%	11.1%	0%	0%	0%	Definitely Disagree	n=9 av.=4.9 dev.=0.3 cf=100.00%

1.12) 1.7 Please comment below on aspects of this teacher's class/seminar teaching you think were particularly helpful.

- - teacher is always there to help if you need it
  - very supportive
  - if you don't understand the work he can sit down and explain it as many times as needed
- Ability to simplify complicated concepts is excellent
- Best teacher I have
- Provides easy to understand examples. Doesn't like to continue until he is sure everyone understands
- The coolest person that uses examples with which you can totally relate and thus better understand and really enjoy this amazing course!

1.13) 1.7b Please comment below on aspects of this teacher's class/seminar teaching you think could be improved.

- N/A
- N/A
- Really the teacher is perfect. Like really. As if he was from a dream or a movie.
- n/a really enjoy teaching style and lessons (my best class teacher)

2. Thank you - Part 1 Complete

Thank you for completing the teacher evaluation of the class/seminar survey.

The next part of the survey asks for your views on the course as a whole. It is not restricted to this particular teacher, but to the entire experience you have had on this course to date.

3. Course Evaluation

Please show the extent of your agreement by selecting the box that reflects your current view of your experience on this course to date:

3.1) 2.1 This course has challenged me to achieve my best work.

Definitely Agree	5	4	3	2	1	Definitely Disagree
	22.2%	44.4%	33.3%	0%	0%	

n=9
av.=3.9
dev.=0.8
cf=66.67%

3.2) 2.2 This course is intellectually stimulating.

Definitely Agree	5	4	3	2	1	Definitely Disagree
	55.6%	22.2%	22.2%	0%	0%	

n=9
av.=4.3
dev.=0.9
cf=77.78%

3.3) 2.3 I have received sufficient advice and guidance in relation to this course to date.

Definitely Agree	5	4	3	2	1	Definitely Disagree
	11.1%	22.2%	55.6%	11.1%	0%	

n=9
av.=3.3
dev.=0.9
cf=33.33%

3.4) 2.4 I am satisfied with the amount of contact time with teachers for this course.

Definitely Agree	5	4	3	2	1	Definitely Disagree
	33.3%	44.4%	22.2%	0%	0%	

n=9
av.=4.1
dev.=0.8
cf=77.78%

3.6) 2.5 I have been able to contact staff about this course when I needed to.

Definitely Agree	5	4	3	2	1	Definitely Disagree
	44.4%	44.4%	11.1%	0%	0%	

n=9
av.=4.3
dev.=0.7
cf=88.89%

Please show the extent of your agreement by selecting the box that reflects your current view of your experience on this course to date:

3.7) 2.6 The criteria used in marking have been clear in advance.

Definitely Agree	5	4	3	2	1	Definitely Disagree
	12.5%	50%	12.5%	25%	0%	

n=8
av.=3.5
dev.=1.1
ab.=1
cf=62.50%

3.8) 2.7 Marking and assessment has been fair.

Definitely Agree	5	4	3	2	1	Definitely Disagree
	33.3%	55.6%	11.1%	0%	0%	

n=9
av.=4.2
dev.=0.7
cf=88.89%

3.9) 2.8 The feedback I received has helped my learning and performance on the course.

Definitely Agree	5	4	3	2	1	Definitely Disagree
	66.7%	22.2%	11.1%	0%	0%	

n=9
av.=4.6
dev.=0.7
cf=88.89%

3.10) 2.9 Do you have a reading list for this course?

Yes	11.1%	n=9
No	88.9%	

3.11) 2.9b The reading list(s) was useful for my learning.

Definitely Agree	5	4	3	2	1	Definitely Disagree
	0%	0%	0%	0%	100%	

n=1
av.=1
dev.=0
cf=0.00%

3.12) 2.9c I have been able to access all my essential readings for this course.

	5	4	3	2	1		
Definitely Agree	25%	0%	25%	0%	50%	Definitely Disagree	n=4 av.=2.5 dev.=1.9 ab.=5 cf=25.00%

3.13) 2.9d I have been able to access all my further readings for this course.

	5	4	3	2	1		
Definitely Agree	25%	0%	25%	0%	50%	Definitely Disagree	n=4 av.=2.5 dev.=1.9 ab.=5 cf=25.00%

3.14) 2.10 I found course materials and activities accessed through Moodle useful for my studies on this course.

	5	4	3	2	1		
Definitely Agree	37.5%	37.5%	25%	0%	0%	Definitely Disagree	n=8 av.=4.1 dev.=0.8 ab.=1 cf=75.00%

3.15) 2.11 The course material provided was useful for my studies and learning.

	5	4	3	2	1		
Definitely Agree	44.4%	44.4%	0%	11.1%	0%	Definitely Disagree	n=9 av.=4.2 dev.=1 cf=88.89%

3.16) 2.12 Do you have lectures for this course?

Yes	100%	n=9
No	0%	

3.17) 2.12b How are lectures delivered on this course:

face-to-face on-campus lectures	0%	n=9
live online lectures (e.g. via Zoom)	77.8%	
pre-recorded lectures	0%	
pre-recorded micro/short/mini lectures	0%	
pre-recorded lectures plus live Q&A	0%	
some combination of the above	22.2%	

3.18) 2.12c I am satisfied with the integration of classes/ seminars with lectures on this course.

	5	4	3	2	1		
Definitely Agree	62.5%	12.5%	12.5%	12.5%	0%	Definitely Disagree	n=8 av.=4.3 dev.=1.2 cf=75.00%

3.19) 2.13 Have you experienced on campus classroom teaching where some of the students are not physically in the classroom but participate via Zoom ('hybrid' classes)

Yes	0%	n=9
No	100%	

3.25) 2.14 Overall, I am satisfied with my experience on this course.

	5	4	3	2	1		
Definitely Agree	33.3%	55.6%	0%	11.1%	0%	Definitely Disagree	n=9 av.=4.1 dev.=0.9 cf=88.89%

3.26) 2.15 Would you recommend this course to other students?

Yes	66.7%	n=9
Maybe	11.1%	
No	22.2%	

3.27) 2.16 Please comment below on aspects of this course you think were particularly good.

- N/A
- Very useful and practical!!!! And I really interesting!

- n/a
- real life case studies

3.28) 2.16b Please comment below on aspects of this course you think could be improved.

- -the start of the course moved very quickly which will tough as already I was trying to adjust to university
- N/A
- There could be given a list of formulas and a summary of all topics useful for tests!
- too mathy

4. Your Information

4.1) 3.1 Which of the reasons given below describe why you are taking the course? *(Please select all that apply)*

It is compulsory for my degree programme	88.9%	n=9
I chose the course as an option for my degree programme	11.1%	
I am interested in the subject matter	11.1%	
It was recommended to me by other students	0%	
It was recommended to me by an academic	0%	
Other	0%	

4.2) 3.1b Was this your 1st, 2nd, 3rd or other choice?

1st choice	100%	n=1
2nd choice	0%	
3rd choice	0%	
Other choice	0%	

4.3) 3.1c In relation to what you wanted to study, how important was choosing this course to you?

Very Important	5	4	3	2	1	Not at all Important
	0%	0%	100%	0%	0%	

n=1
av.=3
dev.=0
cf=0.00%

4.4) 3.2 How many hours of independent study do you put into this course each week outside of lectures, classes, and seminars?

More than 10 hours	0%	n=9
6-10 hours	55.6%	
2-5 hours	33.3%	
Less than 2 hours	11.1%	
None	0%	
N/A	0%	

4.6) 3.4 Do you have any Teaching and Learning Adjustments related to a declared disability?

Yes	0%	n=9
No	100%	

4.9) 3.5 Overall, I have not had problems with digital access to Moodle or other technologies throughout the term.

Definitely Agree	5	4	3	2	1	Definitely Disagree
	55.6%	22.2%	0%	22.2%	0%	

n=9
av.=4.1
dev.=1.3
cf=77.78%

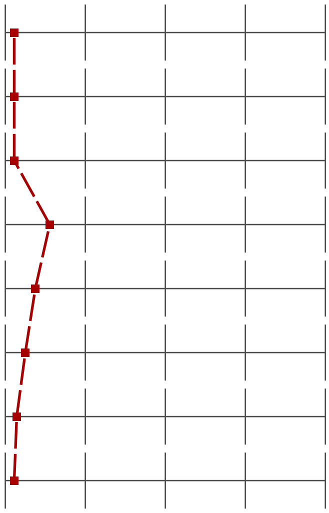
Profile

Subunit: EC - Economics
Name of the instructor: Ghassane Benmir
Name of the course: (Name of the survey) EC1A3.A Microeconomics I - Group 12

Values used in the profile line: Mean

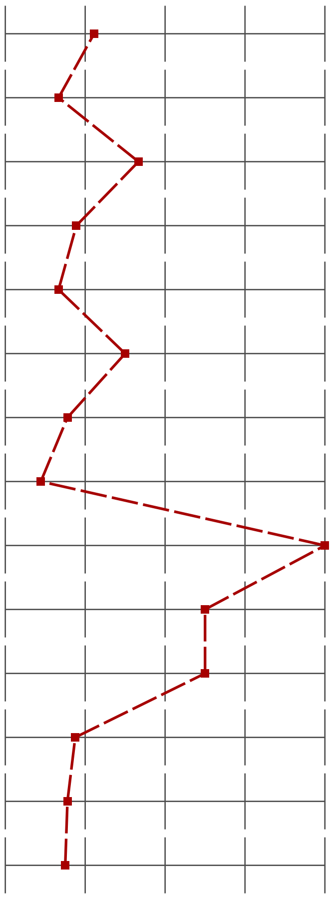
1. Class/Seminar Teacher Evaluation

1.2)	1.1 The teacher communicated ideas and concepts effectively.	Definitely Agree	Definitely Disagree	n=9	av.=4.9
1.3)	1.2 The teacher has improved my understanding of the course content.	Definitely Agree	Definitely Disagree	n=9	av.=4.9
1.4)	1.3 The teacher has made the subject interesting.	Definitely Agree	Definitely Disagree	n=9	av.=4.9
1.6)	1.4b The teacher is good at involving members of the class/seminar.	Definitely Agree	Definitely Disagree	n=9	av.=4.4
1.8)	1.5b Feedback on my work has been timely (typically 3-4 weeks after submission).	Definitely Agree	Definitely Disagree	n=8	av.=4.6
1.9)	1.5c I have received helpful comments on my work.	Definitely Agree	Definitely Disagree	n=8	av.=4.8
1.10)	1.5d I was able to seek further clarification on feedback from the teacher where needed.	Definitely Agree	Definitely Disagree	n=7	av.=4.9
1.11)	1.6 Overall, I am satisfied with the class/seminar teaching by this teacher on this course.	Definitely Agree	Definitely Disagree	n=9	av.=4.9



3. Course Evaluation

3.1)	2.1 This course has challenged me to achieve my best work.	Definitely Agree	Definitely Disagree	n=9	av.=3.9
3.2)	2.2 This course is intellectually stimulating.	Definitely Agree	Definitely Disagree	n=9	av.=4.3
3.3)	2.3 I have received sufficient advice and guidance in relation to this course to date.	Definitely Agree	Definitely Disagree	n=9	av.=3.3
3.4)	2.4 I am satisfied with the amount of contact time with teachers for this course.	Definitely Agree	Definitely Disagree	n=9	av.=4.1
3.6)	2.5 I have been able to contact staff about this course when I needed to.	Definitely Agree	Definitely Disagree	n=9	av.=4.3
3.7)	2.6 The criteria used in marking have been clear in advance.	Definitely Agree	Definitely Disagree	n=8	av.=3.5
3.8)	2.7 Marking and assessment has been fair.	Definitely Agree	Definitely Disagree	n=9	av.=4.2
3.9)	2.8 The feedback I received has helped my learning and performance on the course.	Definitely Agree	Definitely Disagree	n=9	av.=4.6
3.11)	2.9b The reading list(s) was useful for my learning.	Definitely Agree	Definitely Disagree	n=1	av.=1.0
3.12)	2.9c I have been able to access all my essential readings for this course.	Definitely Agree	Definitely Disagree	n=4	av.=2.5
3.13)	2.9d I have been able to access all my further readings for this course.	Definitely Agree	Definitely Disagree	n=4	av.=2.5
3.14)	2.10 I found course materials and activities accessed through Moodle useful for my studies on this course.	Definitely Agree	Definitely Disagree	n=8	av.=4.1
3.15)	2.11 The course material provided was useful for my studies and learning.	Definitely Agree	Definitely Disagree	n=9	av.=4.2
3.18)	2.12c I am satisfied with the integration of classes/ seminars with lectures on this course.	Definitely Agree	Definitely Disagree	n=8	av.=4.3



3.21)	2.13c Overall, I am satisfied with the teaching in these 'hybrid' classes/seminars. (*)	Definitely Agree	Definitely Disagree		
3.22)	2.13d I have been able to participate actively in these classes/seminars. (*)	Definitely Agree	Definitely Disagree		
3.23)	2.13e Thinking about the technologies used (audio, visual), these classes/seminars have worked well. (*)	Definitely Agree	Definitely Disagree		
3.25)	2.14 Overall, I am satisfied with my experience on this course.	Definitely Agree	Definitely Disagree	n=9	av.=4.1

4. Your Information

4.3)	3.1c In relation to what you wanted to study, how important was choosing this course to you?	Very Important	Not at all Important	n=1	av.=3.0
4.5)	3.3 Please rate your own contribution to classes/ seminars. (*)	Very Good	Poor		
4.9)	3.5 Overall, I have not had problems with digital access to Moodle or other technologies throughout the term.	Definitely Agree	Definitely Disagree	n=9	av.=4.1

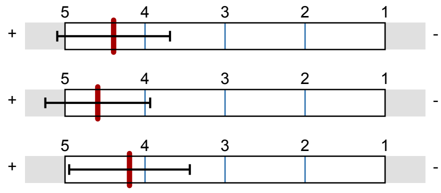
Ghassane Benmir
EC1B3.A Macroeconomics I - Group 2
No. of responses = 12

Overall indicators

Global Index

Class/Seminar Teacher Evaluation (Scale width: 5)

Course Evaluation (Scale width: 5)



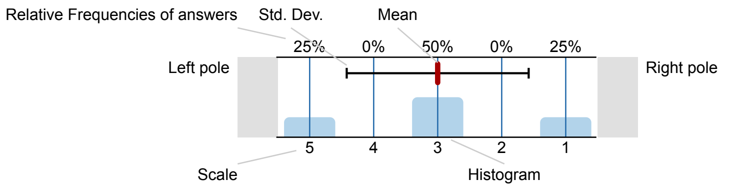
av.=4.4
dev.=0.7

av.=4.6
dev.=0.7

av.=4.2
dev.=0.8

Legend

Question text



n=No. of responses
av.=Mean
dev.=Std. Dev.
ab.=Abstention
cf=Cumulative Frequency

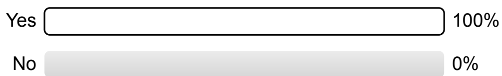
1. Class/Seminar Teacher Evaluation

This survey requests your feedback on two separate aspects of your learning experience, split into three sections. The first section asks for your views on your teacher's class/seminar teaching. The second section asks for your views on the course as a whole at this point in time. Finally, the third section asks for some information about you, to aid analysis.

We recognise that this term has been particularly challenging for everyone due to the wider public health situation, with disruption experienced by both students and teaching staff. The School is continually striving to deliver the best possible educational experience despite these challenges and your views about your learning experience at LSE are a valuable source of information about this. The results will be used to help improve the teaching and learning experience for you and your peers and to identify good practice.

The School assumes that your response is broadly positive if you 'mostly agree' or 'definitely agree' with a statement.

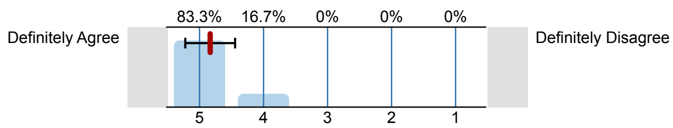
1.1) Do the answers you supply below relate to the teacher from whom you have received the majority of your class/seminar teaching this term? The teacher's name, course title and group number (where relevant) are provided in the invitation email you have received for the survey.



n=9

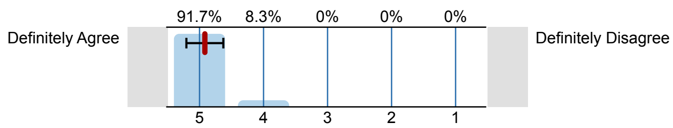
Please show the extent of your agreement by selecting the box that reflects your current view of your class/seminar teacher:

1.2) 1.1 The teacher communicated ideas and concepts effectively.



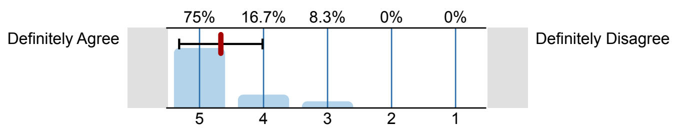
n=12
av.=4.8
dev.=0.4
cf=100.00%

1.3) 1.2 The teacher has improved my understanding of the course content.



n=12
av.=4.9
dev.=0.3
cf=100.00%

1.4) 1.3 The teacher has made the subject interesting.



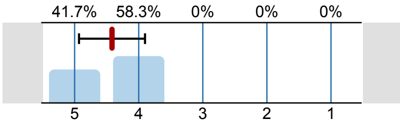
n=12
av.=4.7
dev.=0.7
cf=91.67%

1.5) 1.4 Have you attended classes/seminars for this class/seminar:

on-campus	83.3%	n=12
online	0%	
both	16.7%	

1.6) 1.4b The teacher is good at involving members of the class/seminar.

Definitely Agree



Definitely Disagree

n=12
av.=4.4
dev.=0.5
cf=100.00%

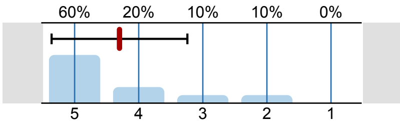
1.7) 1.5 Have you received feedback on your work from this teacher?

Yes	83.3%	n=12
No	16.7%	

Please show the extent of your agreement by selecting the box that reflects your current view of your class/seminar teacher:

1.8) 1.5b Feedback on my work has been timely (typically 3-4 weeks after submission).

Definitely Agree

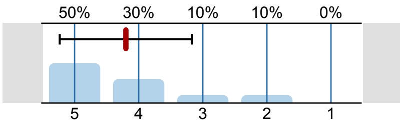


Definitely Disagree

n=10
av.=4.3
dev.=1.1
cf=80.00%

1.9) 1.5c I have received helpful comments on my work.

Definitely Agree

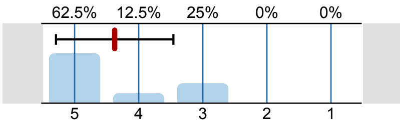


Definitely Disagree

n=10
av.=4.2
dev.=1
cf=80.00%

1.10) 1.5d I was able to seek further clarification on feedback from the teacher where needed.

Definitely Agree



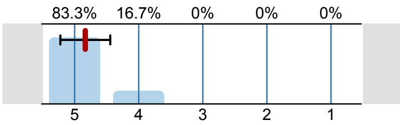
Definitely Disagree

n=8
av.=4.4
dev.=0.9
ab.=2
cf=75.00%

Please show the extent of your agreement by selecting the box that reflects your current view of your class/seminar teacher:

1.11) 1.6 Overall, I am satisfied with the class/seminar teaching by this teacher on this course.

Definitely Agree



Definitely Disagree

n=12
av.=4.8
dev.=0.4
cf=100.00%

1.12) 1.7 Please comment below on aspects of this teacher's class/seminar teaching you think were particularly helpful.

- 1. Ghassane always provided review of key concepts and challenge us to understand the working of the various models we learned în an engaging manner.
  2. Discussion about real life implications made the class fell like it was adding an additional element to lectures and reading.
- Engaging
- Going through this week's material at the start of the lecture
- I think going beyond the course and providing information about external aspects also helped gain a deeper understanding of the course.
- Well-explained, helps me thoroughly understand the content

1.13) 1.7b Please comment below on aspects of this teacher's class/seminar teaching you think could be improved.

- Give more feedback on individual questions rather than just giving a mark for most questions
- Going through the parts in class while doing them on the board (step by step) as opposed to the current method would be better I think.
- Specific to the course material

2. Thank you - Part 1 Complete

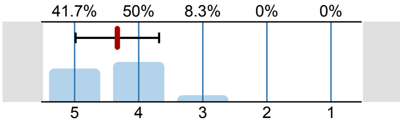
Thank you for completing the teacher evaluation of the class/seminar survey.

The next part of the survey asks for your views on the course as a whole. It is not restricted to this particular teacher, but to the entire experience you have had on this course to date.

3. Course Evaluation

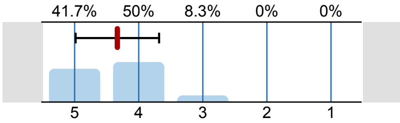
Please show the extent of your agreement by selecting the box that reflects your current view of your experience on this course to date:

3.1) 2.1 This course has challenged me to achieve my best work.

Definitely Agree  Definitely Disagree

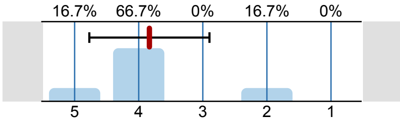
n=12
av.=4.3
dev.=0.7
cf=91.67%

3.2) 2.2 This course is intellectually stimulating.

Definitely Agree  Definitely Disagree

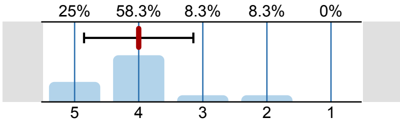
n=12
av.=4.3
dev.=0.7
cf=91.67%

3.3) 2.3 I have received sufficient advice and guidance in relation to this course to date.

Definitely Agree  Definitely Disagree

n=12
av.=3.8
dev.=0.9
cf=83.33%

3.4) 2.4 I am satisfied with the amount of contact time with teachers for this course.

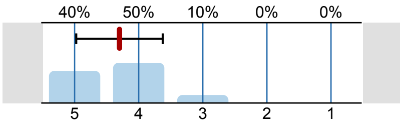
Definitely Agree  Definitely Disagree

n=12
av.=4
dev.=0.9
cf=83.33%

3.5) 2.4b Please comment below about why contact time with teachers has been less than satisfactory.

- I would be great to have more contact time with teachers as the content is very rich.

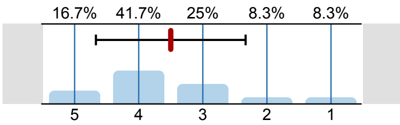
3.6) 2.5 I have been able to contact staff about this course when I needed to.

Definitely Agree  Definitely Disagree

n=10
av.=4.3
dev.=0.7
ab.=2
cf=90.00%

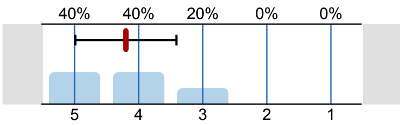
Please show the extent of your agreement by selecting the box that reflects your current view of your experience on this course to date:

3.7) 2.6 The criteria used in marking have been clear in advance.

Definitely Agree  Definitely Disagree

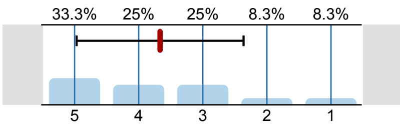
n=12
av.=3.5
dev.=1.2
cf=58.33%

3.8) 2.7 Marking and assessment has been fair.

Definitely Agree  Definitely Disagree

n=10
av.=4.2
dev.=0.8
ab.=2
cf=80.00%

3.9) 2.8 The feedback I received has helped my learning and performance on the course.

Definitely Agree  Definitely Disagree

n=12
av.=3.7
dev.=1.3
cf=58.33%

3.10) 2.9 Do you have a reading list for this course?

Yes 91.7%
No 8.3%

n=12

3.11) 2.9b The reading list(s) was useful for my learning.

Definitely Agree	5	4	3	2	1	Definitely Disagree	
	72.7%	27.3%	0%	0%	0%		n=11 av.=4.7 dev.=0.5 cf=100.00%

3.12) 2.9c I have been able to access all my essential readings for this course.

Definitely Agree	5	4	3	2	1	Definitely Disagree	
	66.7%	33.3%	0%	0%	0%		n=12 av.=4.7 dev.=0.5 cf=100.00%

3.13) 2.9d I have been able to access all my further readings for this course.

Definitely Agree	5	4	3	2	1	Definitely Disagree	
	70%	30%	0%	0%	0%		n=10 av.=4.7 dev.=0.5 ab.=2 cf=100.00%

3.14) 2.10 I found course materials and activities accessed through Moodle useful for my studies on this course.

Definitely Agree	5	4	3	2	1	Definitely Disagree	
	58.3%	41.7%	0%	0%	0%		n=12 av.=4.6 dev.=0.5 cf=100.00%

3.15) 2.11 The course material provided was useful for my studies and learning.

Definitely Agree	5	4	3	2	1	Definitely Disagree	
	50%	50%	0%	0%	0%		n=12 av.=4.5 dev.=0.5 cf=100.00%

3.16) 2.12 Do you have lectures for this course?

Yes	100%	n=12
No	0%	

3.17) 2.12b How are lectures delivered on this course:

face-to-face on-campus lectures	0%	n=12
live online lectures (e.g. via Zoom)	91.7%	
pre-recorded lectures	0%	
pre-recorded micro/short/mini lectures	0%	
pre-recorded lectures plus live Q&A	0%	
some combination of the above	8.3%	

3.18) 2.12c I am satisfied with the integration of classes/ seminars with lectures on this course.

Definitely Agree	5	4	3	2	1	Definitely Disagree	
	41.7%	58.3%	0%	0%	0%		n=12 av.=4.4 dev.=0.5 cf=100.00%

3.19) 2.13 Have you experienced on campus classroom teaching where some of the students are not physically in the classroom but participate via Zoom (‘hybrid’ classes)

Yes	0%	n=12
No	100%	

3.25) 2.14 Overall, I am satisfied with my experience on this course.

Definitely Agree	5	4	3	2	1	Definitely Disagree	
	41.7%	58.3%	0%	0%	0%		n=12 av.=4.4 dev.=0.5 cf=100.00%

3.26) 2.15 Would you recommend this course to other students?

Yes	66.7%	n=12
Maybe	33.3%	
No	0%	

3.27) 2.16 Please comment below on aspects of this course you think were particularly good.

- The pacing of the content has been good and each week feels like it is distinct in the way it evolves from the previous week
- They were intellectual stimulating as it helped me understand the fundamentals of macroeconomics and the various aspects that are involved in it.
- Very engaging class

3.28) 2.16b Please comment below on aspects of this course you think could be improved.

- More specific to fours ematerial
- The problem sets sometimes involved putting numbers into Excel and then copying them out again which can be a bit boring
- The readings are sometimes long and the lectures aren't long enough to cover the content.

4. Your Information

4.1) 3.1 Which of the reasons given below describe why you are taking the course? *(Please select all that apply)*

It is compulsory for my degree programme	100%	n=12
I chose the course as an option for my degree programme	0%	
I am interested in the subject matter	16.7%	
It was recommended to me by other students	0%	
It was recommended to me by an academic	0%	
Other	0%	

4.4) 3.2 How many hours of independent study do you put into this course each week outside of lectures, classes, and seminars?

More than 10 hours	0%	n=11
6-10 hours	45.5%	
2-5 hours	54.5%	
Less than 2 hours	0%	
None	0%	
N/A	0%	

4.6) 3.4 Do you have any Teaching and Learning Adjustments related to a declared disability?

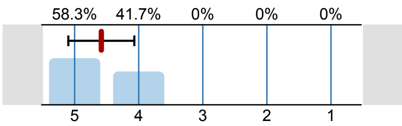
Yes	16.7%	n=12
No	83.3%	

4.7) 3.4b Have any adjustments highlighted in your Inclusion Plan not been addressed in this course?

Some adjustments have not been addressed	0%	n=2
All the adjustments were addressed, or none of the adjustments were relevant to this course	100%	

4.9) 3.5 Overall, I have not had problems with digital access to Moodle or other technologies throughout the term.

Definitely Agree



Definitely Disagree

n=12
av.=4.6
dev.=0.5
cf=100.00%

Profile

Subunit: EC - Economics
Name of the instructor: Ghassane Benmir
Name of the course: (Name of the survey) EC1B3.A Macroeconomics I - Group 2

Values used in the profile line: Mean

1. Class/Seminar Teacher Evaluation

1.2)	1.1 The teacher communicated ideas and concepts effectively.	Definitely Agree	Definitely Disagree	n=12	av.=4.8
1.3)	1.2 The teacher has improved my understanding of the course content.	Definitely Agree	Definitely Disagree	n=12	av.=4.9
1.4)	1.3 The teacher has made the subject interesting.	Definitely Agree	Definitely Disagree	n=12	av.=4.7
1.6)	1.4b The teacher is good at involving members of the class/seminar.	Definitely Agree	Definitely Disagree	n=12	av.=4.4
1.8)	1.5b Feedback on my work has been timely (typically 3-4 weeks after submission).	Definitely Agree	Definitely Disagree	n=10	av.=4.3
1.9)	1.5c I have received helpful comments on my work.	Definitely Agree	Definitely Disagree	n=10	av.=4.2
1.10)	1.5d I was able to seek further clarification on feedback from the teacher where needed.	Definitely Agree	Definitely Disagree	n=8	av.=4.4
1.11)	1.6 Overall, I am satisfied with the class/seminar teaching by this teacher on this course.	Definitely Agree	Definitely Disagree	n=12	av.=4.8

3. Course Evaluation

3.1)	2.1 This course has challenged me to achieve my best work.	Definitely Agree	Definitely Disagree	n=12	av.=4.3
3.2)	2.2 This course is intellectually stimulating.	Definitely Agree	Definitely Disagree	n=12	av.=4.3
3.3)	2.3 I have received sufficient advice and guidance in relation to this course to date.	Definitely Agree	Definitely Disagree	n=12	av.=3.8
3.4)	2.4 I am satisfied with the amount of contact time with teachers for this course.	Definitely Agree	Definitely Disagree	n=12	av.=4.0
3.6)	2.5 I have been able to contact staff about this course when I needed to.	Definitely Agree	Definitely Disagree	n=10	av.=4.3
3.7)	2.6 The criteria used in marking have been clear in advance.	Definitely Agree	Definitely Disagree	n=12	av.=3.5
3.8)	2.7 Marking and assessment has been fair.	Definitely Agree	Definitely Disagree	n=10	av.=4.2
3.9)	2.8 The feedback I received has helped my learning and performance on the course.	Definitely Agree	Definitely Disagree	n=12	av.=3.7
3.11)	2.9b The reading list(s) was useful for my learning.	Definitely Agree	Definitely Disagree	n=11	av.=4.7
3.12)	2.9c I have been able to access all my essential readings for this course.	Definitely Agree	Definitely Disagree	n=12	av.=4.7
3.13)	2.9d I have been able to access all my further readings for this course.	Definitely Agree	Definitely Disagree	n=10	av.=4.7
3.14)	2.10 I found course materials and activities accessed through Moodle useful for my studies on this course.	Definitely Agree	Definitely Disagree	n=12	av.=4.6
3.15)	2.11 The course material provided was useful for my studies and learning.	Definitely Agree	Definitely Disagree	n=12	av.=4.5
3.18)	2.12c I am satisfied with the integration of classes/ seminars with lectures on this course.	Definitely Agree	Definitely Disagree	n=12	av.=4.4

3.21)	2.13c Overall, I am satisfied with the teaching in these 'hybrid' classes/seminars. (*)	Definitely Agree		Definitely Disagree		
3.22)	2.13d I have been able to participate actively in these classes/seminars. (*)	Definitely Agree		Definitely Disagree		
3.23)	2.13e Thinking about the technologies used (audio, visual), these classes/seminars have worked well. (*)	Definitely Agree		Definitely Disagree		
3.25)	2.14 Overall, I am satisfied with my experience on this course.	Definitely Agree		Definitely Disagree	n=12	av.=4.4

4. Your Information

4.3)	3.1c In relation to what you wanted to study, how important was choosing this course to you? (*)	Very Important		Not at all Important		
4.5)	3.3 Please rate your own contribution to classes/ seminars. (*)	Very Good		Poor		
4.9)	3.5 Overall, I have not had problems with digital access to Moodle or other technologies throughout the term.	Definitely Agree		Definitely Disagree	n=12	av.=4.6

Ghassane Benmir

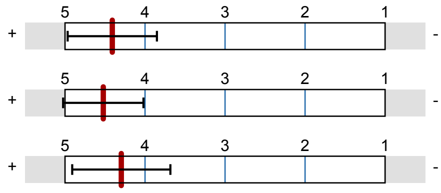
EC1B5.A Macroeconomics I - Group 5
No. of responses = 9

Overall indicators

Global Index

Class/Seminar Teacher Evaluation (Scale width: 5)

Course Evaluation (Scale width: 5)



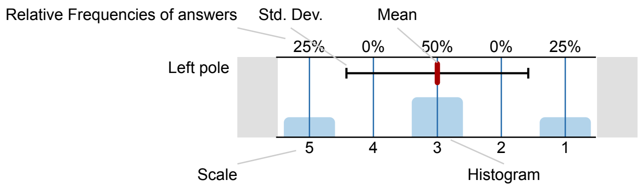
av.=4.4
dev.=0.6

av.=4.5
dev.=0.5

av.=4.3
dev.=0.6

Legend

Question text



n=No. of responses
av.=Mean
dev.=Std. Dev.
ab.=Abstention
cf=Cumulative Frequency

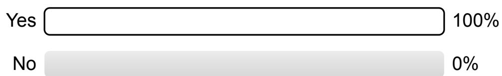
1. Class/Seminar Teacher Evaluation

This survey requests your feedback on two separate aspects of your learning experience, split into three sections. The first section asks for your views on your teacher's class/seminar teaching. The second section asks for your views on the course as a whole at this point in time. Finally, the third section asks for some information about you, to aid analysis.

We recognise that this term has been particularly challenging for everyone due to the wider public health situation, with disruption experienced by both students and teaching staff. The School is continually striving to deliver the best possible educational experience despite these challenges and your views about your learning experience at LSE are a valuable source of information about this. The results will be used to help improve the teaching and learning experience for you and your peers and to identify good practice.

The School assumes that your response is broadly positive if you 'mostly agree' or 'definitely agree' with a statement.

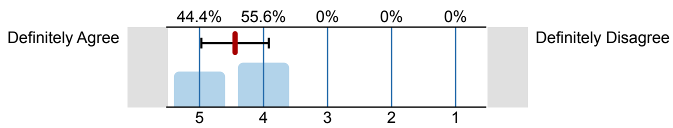
1.1) Do the answers you supply below relate to the teacher from whom you have received the majority of your class/seminar teaching this term? The teacher's name, course title and group number (where relevant) are provided in the invitation email you have received for the survey.



n=8

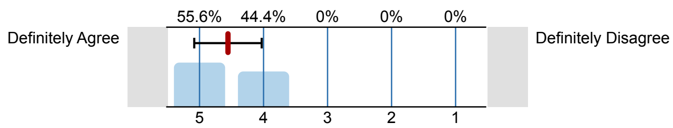
Please show the extent of your agreement by selecting the box that reflects your current view of your class/seminar teacher:

1.2) 1.1 The teacher communicated ideas and concepts effectively.



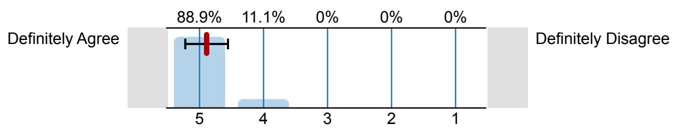
n=9
av.=4.4
dev.=0.5
cf=100.00%

1.3) 1.2 The teacher has improved my understanding of the course content.



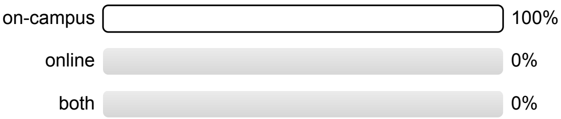
n=9
av.=4.6
dev.=0.5
cf=100.00%

1.4) 1.3 The teacher has made the subject interesting.



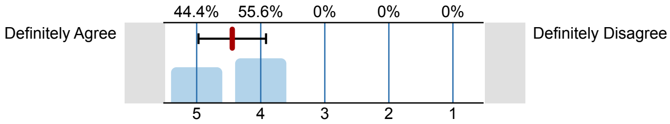
n=9
av.=4.9
dev.=0.3
cf=100.00%

1.5) 1.4 Have you attended classes/seminars for this class/seminar:



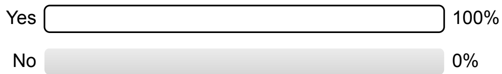
n=9

1.6) 1.4b The teacher is good at involving members of the class/seminar.



n=9
av.=4.4
dev.=0.5
cf=100.00%

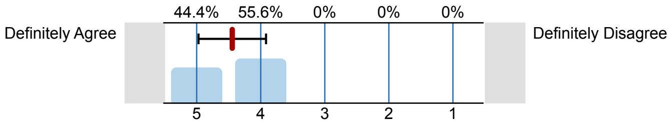
1.7) 1.5 Have you received feedback on your work from this teacher?



n=9

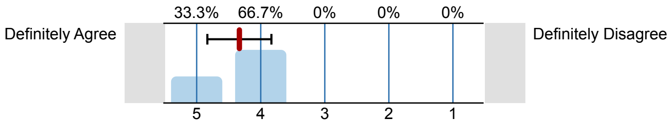
Please show the extent of your agreement by selecting the box that reflects your current view of your class/seminar teacher:

1.8) 1.5b Feedback on my work has been timely (typically 3-4 weeks after submission).



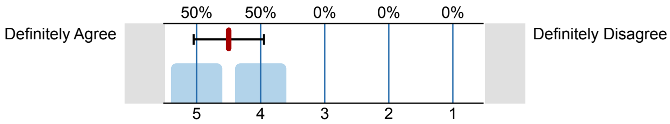
n=9
av.=4.4
dev.=0.5
cf=100.00%

1.9) 1.5c I have received helpful comments on my work.



n=9
av.=4.3
dev.=0.5
cf=100.00%

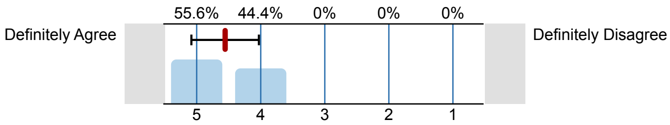
1.10) 1.5d I was able to seek further clarification on feedback from the teacher where needed.



n=6
av.=4.5
dev.=0.5
ab.=3
cf=100.00%

Please show the extent of your agreement by selecting the box that reflects your current view of your class/seminar teacher:

1.11) 1.6 Overall, I am satisfied with the class/seminar teaching by this teacher on this course.



n=9
av.=4.6
dev.=0.5
cf=100.00%

1.12) 1.7 Please comment below on aspects of this teacher's class/seminar teaching you think were particularly helpful.

- Explanation of quiz answers and class discussions are easy to follow and understand. Content overview on the powerpoint slides at the beginning of each class are particularly helpful.
- Great teaching, makes the subject very easy to understand. Easy vocabulary no complexity.
- He is good at explaining the concepts of the course well
- He is more conceptual in explaining the ideas and theories in class, as opposed to my first term where the teacher just went through worked materials.
- He is very elaborate on connecting the things we learn in class with what is relevant in the world today, making the subject very interesting. Very knowledgeable indeed.
- going over the quizzes

1.13) 1.7b Please comment below on aspects of this teacher's class/seminar teaching you think could be improved.

- Already very very good!!!
- Perhaps, one thing that can be improved is in responding on all emails, even if it is just to note something.
- discussing more key concepts from the lecture in the seminar to make sure the basics are understood

2. Thank you - Part 1 Complete

Thank you for completing the teacher evaluation of the class/seminar survey.

The next part of the survey asks for your views on the course as a whole. It is not restricted to this particular teacher, but to the entire experience you have had on this course to date.

3. Course Evaluation

Please show the extent of your agreement by selecting the box that reflects your current view of your experience on this course to date:

3.1) 2.1 This course has challenged me to achieve my best work.

Definitely Agree	5	4	3	2	1	Definitely Disagree
	33.3%	66.7%	0%	0%	0%	

n=9, av.=4.3, dev.=0.5, cf=100.00%

3.2) 2.2 This course is intellectually stimulating.

Definitely Agree	5	4	3	2	1	Definitely Disagree
	33.3%	66.7%	0%	0%	0%	

n=9, av.=4.3, dev.=0.5, cf=100.00%

3.3) 2.3 I have received sufficient advice and guidance in relation to this course to date.

Definitely Agree	5	4	3	2	1	Definitely Disagree
	33.3%	55.6%	0%	11.1%	0%	

n=9, av.=4.1, dev.=0.9, cf=88.89%

3.4) 2.4 I am satisfied with the amount of contact time with teachers for this course.

Definitely Agree	5	4	3	2	1	Definitely Disagree
	33.3%	44.4%	22.2%	0%	0%	

n=9, av.=4.1, dev.=0.8, cf=77.78%

3.6) 2.5 I have been able to contact staff about this course when I needed to.

Definitely Agree	5	4	3	2	1	Definitely Disagree
	50%	37.5%	12.5%	0%	0%	

n=8, av.=4.4, dev.=0.7, ab.=1, cf=87.50%

Please show the extent of your agreement by selecting the box that reflects your current view of your experience on this course to date:

3.7) 2.6 The criteria used in marking have been clear in advance.

Definitely Agree	5	4	3	2	1	Definitely Disagree
	33.3%	22.2%	33.3%	11.1%	0%	

n=9, av.=3.8, dev.=1.1, cf=55.56%

3.8) 2.7 Marking and assessment has been fair.

Definitely Agree	5	4	3	2	1	Definitely Disagree
	55.6%	33.3%	11.1%	0%	0%	

n=9, av.=4.4, dev.=0.7, cf=88.89%

3.9) 2.8 The feedback I received has helped my learning and performance on the course.

Definitely Agree	5	4	3	2	1	Definitely Disagree
	33.3%	55.6%	11.1%	0%	0%	

n=9, av.=4.2, dev.=0.7, cf=88.89%

3.10) 2.9 Do you have a reading list for this course?

Yes	22.2%
No	77.8%

n=9

3.11) 2.9b The reading list(s) was useful for my learning.

Definitely Agree	5	4	3	2	1	Definitely Disagree
	0%	0%	100%	0%	0%	

n=1, av.=3, dev.=0, ab.=1, cf=0.00%

3.12) 2.9c I have been able to access all my essential readings for this course.

Definitely Agree	5	4	3	2	1	Definitely Disagree
	50%	50%	0%	0%	0%	

n=4
av.=4.5
dev.=0.6
ab.=5
cf=100.00%

3.13) 2.9d I have been able to access all my further readings for this course.

Definitely Agree	5	4	3	2	1	Definitely Disagree
	50%	50%	0%	0%	0%	

n=4
av.=4.5
dev.=0.6
ab.=5
cf=100.00%

3.14) 2.10 I found course materials and activities accessed through Moodle useful for my studies on this course.

Definitely Agree	5	4	3	2	1	Definitely Disagree
	80%	20%	0%	0%	0%	

n=5
av.=4.8
dev.=0.4
ab.=4
cf=100.00%

3.15) 2.11 The course material provided was useful for my studies and learning.

Definitely Agree	5	4	3	2	1	Definitely Disagree
	80%	20%	0%	0%	0%	

n=5
av.=4.8
dev.=0.4
ab.=4
cf=100.00%

3.16) 2.12 Do you have lectures for this course?

Yes	100%
No	0%

n=8

3.17) 2.12b How are lectures delivered on this course:

face-to-face on-campus lectures	0%
live online lectures (e.g. via Zoom)	87.5%
pre-recorded lectures	0%
pre-recorded micro/short/mini lectures	0%
pre-recorded lectures plus live Q&A	0%
some combination of the above	12.5%

n=8

3.18) 2.12c I am satisfied with the integration of classes/ seminars with lectures on this course.

Definitely Agree	5	4	3	2	1	Definitely Disagree
	50%	50%	0%	0%	0%	

n=8
av.=4.5
dev.=0.5
cf=100.00%

3.19) 2.13 Have you experienced on campus classroom teaching where some of the students are not physically in the classroom but participate via Zoom ('hybrid' classes)

Yes	11.1%
No	88.9%

n=9

3.20) 2.13b Have you participated in these sessions

in the classroom	100%
via Zoom	0%
both	0%

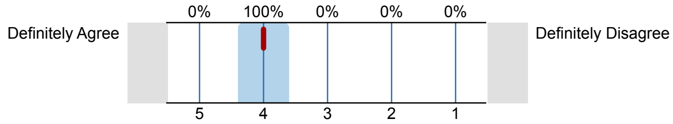
n=1

3.21) 2.13c Overall, I am satisfied with the teaching in these 'hybrid' classes/seminars.

Definitely Agree	5	4	3	2	1	Definitely Disagree
	0%	100%	0%	0%	0%	

n=1
av.=4
dev.=0
cf=100.00%

3.22) 2.13d I have been able to participate actively in these classes/seminars.

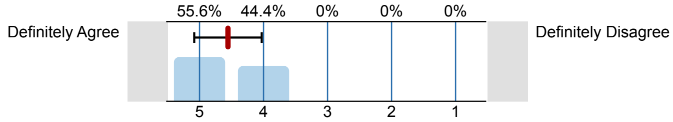


n=1
av.=4
dev.=0
cf=100.00%

3.24) 2.13f Please add any other comments on how these sessions have worked

- The teacher shared the screen, which I think is useful.

3.25) 2.14 Overall, I am satisfied with my experience on this course.



n=9
av.=4.6
dev.=0.5
cf=100.00%

3.26) 2.15 Would you recommend this course to other students?

Yes	77.8%	n=9
Maybe	22.2%	
No	0%	

3.27) 2.16 Please comment below on aspects of this course you think were particularly good.

- It is just very relevant with the world today, and the course brings notable people to attend class.
- everything is perfect!!!
- the way the program is structured ie how each topic links with the previous

3.28) 2.16b Please comment below on aspects of this course you think could be improved.

- already very good !!!
- online zoom classes can often be challenging due to the speed of the content covered. perhaps prerecording could be more useful for students.

4. Your Information

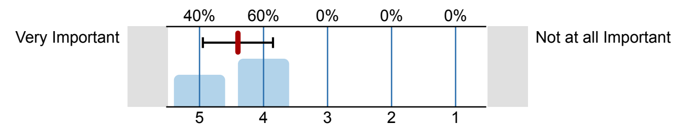
4.1) 3.1 Which of the reasons given below describe why you are taking the course? *(Please select all that apply)*

It is compulsory for my degree programme	33.3%	n=9
I chose the course as an option for my degree programme	55.6%	
I am interested in the subject matter	55.6%	
It was recommended to me by other students	11.1%	
It was recommended to me by an academic	11.1%	
Other	22.2%	

4.2) 3.1b Was this your 1st, 2nd, 3rd or other choice?

1st choice	100%	n=5
2nd choice	0%	
3rd choice	0%	
Other choice	0%	

4.3) 3.1c In relation to what you wanted to study, how important was choosing this course to you?



n=5
av.=4.4
dev.=0.5
cf=100.00%

4.4) 3.2 How many hours of independent study do you put into this course each week outside of lectures, classes, and seminars?

More than 10 hours	0%	n=9
6-10 hours	11.1%	
2-5 hours	66.7%	
Less than 2 hours	22.2%	
None	0%	
N/A	0%	

4.6) 3.4 Do you have any Teaching and Learning Adjustments related to a declared disability?

Yes	11.1%	n=9
No	88.9%	

4.7) 3.4b Have any adjustments highlighted in your Inclusion Plan not been addressed in this course?

Some adjustments have not been addressed	100%	n=1
All the adjustments were addressed, or none of the adjustments were relevant to this course	0%	

4.8) 3.4c If some adjustments were not addressed, please provide further details

- still waiting on a reply from the LSE team after reporting my concussion that I got two weeks ago which has impaired my capabilities to concentrate and work for long periods of time.

4.9) 3.5 Overall, I have not had problems with digital access to Moodle or other technologies throughout the term.

	5	4	3	2	1		
Definitely Agree	100%	0%	0%	0%	0%	Definitely Disagree	n=9 av.=5 dev.=0 cf=100.00%

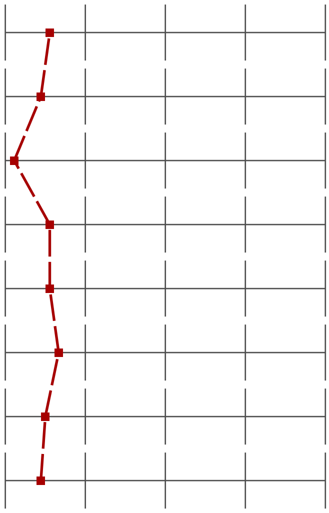
Profile

Subunit: EC - Economics
Name of the instructor: Ghassane Benmir
Name of the course: (Name of the survey) EC1B5.A Macroeconomics I - Group 5

Values used in the profile line: Mean

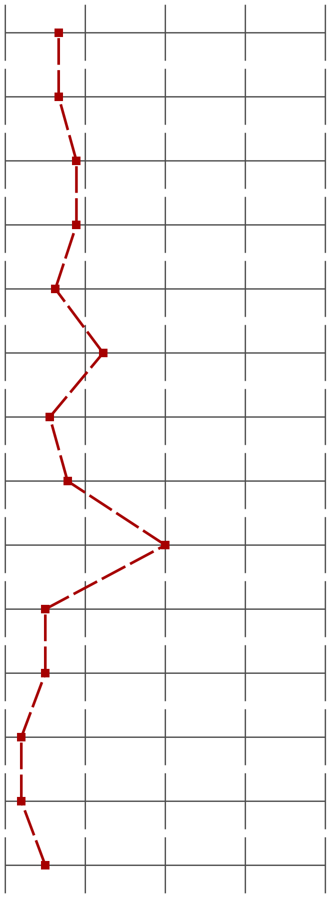
1. Class/Seminar Teacher Evaluation

1.2)	1.1 The teacher communicated ideas and concepts effectively.	Definitely Agree	Definitely Disagree	n=9	av.=4.4
1.3)	1.2 The teacher has improved my understanding of the course content.	Definitely Agree	Definitely Disagree	n=9	av.=4.6
1.4)	1.3 The teacher has made the subject interesting.	Definitely Agree	Definitely Disagree	n=9	av.=4.9
1.6)	1.4b The teacher is good at involving members of the class/seminar.	Definitely Agree	Definitely Disagree	n=9	av.=4.4
1.8)	1.5b Feedback on my work has been timely (typically 3-4 weeks after submission).	Definitely Agree	Definitely Disagree	n=9	av.=4.4
1.9)	1.5c I have received helpful comments on my work.	Definitely Agree	Definitely Disagree	n=9	av.=4.3
1.10)	1.5d I was able to seek further clarification on feedback from the teacher where needed.	Definitely Agree	Definitely Disagree	n=6	av.=4.5
1.11)	1.6 Overall, I am satisfied with the class/seminar teaching by this teacher on this course.	Definitely Agree	Definitely Disagree	n=9	av.=4.6

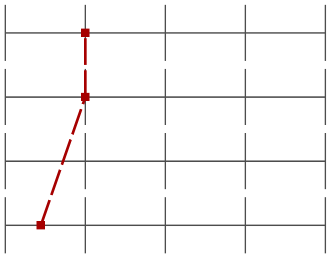


3. Course Evaluation

3.1)	2.1 This course has challenged me to achieve my best work.	Definitely Agree	Definitely Disagree	n=9	av.=4.3
3.2)	2.2 This course is intellectually stimulating.	Definitely Agree	Definitely Disagree	n=9	av.=4.3
3.3)	2.3 I have received sufficient advice and guidance in relation to this course to date.	Definitely Agree	Definitely Disagree	n=9	av.=4.1
3.4)	2.4 I am satisfied with the amount of contact time with teachers for this course.	Definitely Agree	Definitely Disagree	n=9	av.=4.1
3.6)	2.5 I have been able to contact staff about this course when I needed to.	Definitely Agree	Definitely Disagree	n=8	av.=4.4
3.7)	2.6 The criteria used in marking have been clear in advance.	Definitely Agree	Definitely Disagree	n=9	av.=3.8
3.8)	2.7 Marking and assessment has been fair.	Definitely Agree	Definitely Disagree	n=9	av.=4.4
3.9)	2.8 The feedback I received has helped my learning and performance on the course.	Definitely Agree	Definitely Disagree	n=9	av.=4.2
3.11)	2.9b The reading list(s) was useful for my learning.	Definitely Agree	Definitely Disagree	n=1	av.=3.0
3.12)	2.9c I have been able to access all my essential readings for this course.	Definitely Agree	Definitely Disagree	n=4	av.=4.5
3.13)	2.9d I have been able to access all my further readings for this course.	Definitely Agree	Definitely Disagree	n=4	av.=4.5
3.14)	2.10 I found course materials and activities accessed through Moodle useful for my studies on this course.	Definitely Agree	Definitely Disagree	n=5	av.=4.8
3.15)	2.11 The course material provided was useful for my studies and learning.	Definitely Agree	Definitely Disagree	n=5	av.=4.8
3.18)	2.12c I am satisfied with the integration of classes/ seminars with lectures on this course.	Definitely Agree	Definitely Disagree	n=8	av.=4.5

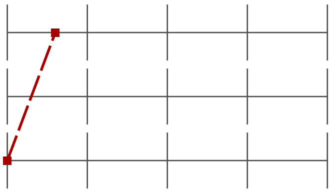


3.21)	2.13c Overall, I am satisfied with the teaching in these ‘hybrid’ classes/seminars.	Definitely Agree	Definitely Disagree	n=1	av.=4.0
3.22)	2.13d I have been able to participate actively in these classes/seminars.	Definitely Agree	Definitely Disagree	n=1	av.=4.0
3.23)	2.13e Thinking about the technologies used (audio, visual), these classes/seminars have worked well. (*)	Definitely Agree	Definitely Disagree		
3.25)	2.14 Overall, I am satisfied with my experience on this course.	Definitely Agree	Definitely Disagree	n=9	av.=4.6



4. Your Information

4.3)	3.1c In relation to what you wanted to study, how important was choosing this course to you?	Very Important	Not at all Important	n=5	av.=4.4
4.5)	3.3 Please rate your own contribution to classes/ seminars. (*)	Very Good	Poor		
4.9)	3.5 Overall, I have not had problems with digital access to Moodle or other technologies throughout the term.	Definitely Agree	Definitely Disagree	n=9	av.=5.0



The Distributional Costs of Net-Zero: A Heterogeneous Agent Perspective

Ghassane Benmir*† Josselin Roman†

(First draft: April 2022)

This version is of: November 6, 2022

Most up-to-date version

Here

Abstract

This paper investigates the distributional impacts of implementing the net-zero emissions target in the U.S. for the 2050 horizon. We model a heterogeneous household economy and show that 2050 net-zero policy is welfare enhancing in the long run, but induces short/medium-run welfare costs. We quantify this trade-off by a 35.2% welfare gain (compared to the laissez-faire) in the long run and a 24.5% loss over the transition. We then show how distributing revenue from the carbon policy could partially offset consumption losses and smooth the net-zero transition. We also extend our analysis to the cases of: i) sticky prices, showing how net-zero emissions induces inflationary pressure over the long run, which could represent a challenge for monetary policy conduction in a world with high inflation, and ii) abatement learning, showing how green innovation decreases carbon prices and boosts consumption over the transition.

Keywords: Net-zero carbon policy, Transition pathways, HANK, Income and wealth inequalities, Welfare, Energy prices.

JEL: Q58, G12, E32.

*London School of Economics and Political Science; email: g.benmir@lse.ac.uk

†PSL Research – Paris Dauphine University.

We are grateful for funding and support for this research from the LSE - Grantham Research Institute, the ESRC through the Centre for Climate Change Economics and Policy, and PSL Research University - Paris Dauphine. The authors are also extremely grateful to Robin Burgess, Eve Caroli, Wouter Den Haan, Simon Dietz, Stephie Fried, Lars Peter Hansen, Daniel Herrera, Ivan Jaccard, Tierra McMahon, Antonio Mele, Kurt Mitman, Ben Moll, Rachel Ngai, Luca Taschini, Farid Toubal, Fabien Tripier, Quentin Vandeweyer, Pietro Veronesi, Gauthier Vermandel, as well as participants from The University of Chicago MFR Program, PSL Reseach – Paris Dauphine Economics Seminar, and the LSE Seminar Series for useful discussions and for providing comments on an earlier draft. All errors and omissions are our own. The usual disclaimers apply.

1 Introduction

As carbon prices reach historical heights (figure XXIV), one of the major concerns with the 2050 net-zero emissions target lies in its potential distributional impacts. The example of the Yellow Vest Crisis (*Les Gilets Jaunes*) in France and Canada, to name only two instances of carbon-tax induced social upheaval, highlights the importance of accounting for distributional impacts when setting a carbon price, impacts of which may otherwise impede its implementation.

While a number of macroeconomic climate policy analyses include heterogeneity in the production sector or in climate damages, the literature mostly relies on a representative household sector and suffers from an absence of frameworks that include full household heterogeneity. Little is known about the properties of consumption and saving behavior in the presence of both: i) climate dynamics, and ii) income and wealth heterogeneity; and even less is known about such behavior under the presence of borrowing constraints.

In this paper we investigate the distributional impacts of setting a net-zero carbon policy by 2050 in the U.S. and elucidate the roles fiscal redistribution, inflation dynamics, and green innovation play over the transition to net-zero. To this end, we develop a heterogeneous agent macroeconomic model that accounts for climate dynamics and allows for studying the distributional impacts of carbon net-zero policy. We first contrast carbon-MIT shock simulations with empirical findings on the California cap-and-trade market to ensure that the model responses are consistent with empirical findings. Then we compute transition pathways toward the net-zero 2050 emissions target and investigate the impacts of the environmental policy on the joint distribution of income and wealth.

Our main finding is that the net-zero emissions policy leads to contrasting short/medium-run and long-run outcomes. In particular, we show that the net-zero policy is ultimately welfare-enhancing over the long-run, while it decreases welfare (compared to the laissez-faire scenario) over the transition period (i.e. 2022-2050). These welfare results are mainly driven by wealth distribution dynamics shifting toward the borrowing constraint. We begin by showing the important role climate dynamics play over the transition and how they shape the joint distribution dynamics over the long run. We find that accounting for climate dynamics, in a laissez-faire scenario, reduces asset holdings over the long run for all income and wealth quantiles. In contrast, implementing a carbon policy that aims to achieve the net-zero target by 2050—which would allow for temperature to stay below 2^{o}C over the long run—destroys wealth over the transition (i.e. between 2022 and 2050). Households engage in precautionary savings[1] as they expect carbon prices to significantly increase over the transition, which mechanically raises capital holdings in the first few years. However, as carbon prices increase, more households join the borrowing constraint, ultimately increasing by 6-10 percent the total number of households financially constrained when compared to the laissez-faire scenario. Over the long run, the joint distribution of income and wealth shifts to the right compared to the laissez-faire case (i.e. more households move away from the borrowing constraint and hold higher levels of capital) as temperature damages are now offset. Therefore, our framework uncovers (and quantifies) a clear trade-off between the long-run welfare benefits of carbon reduction policies and the short-run welfare/distributional costs of the net-zero transition, which ought to be taken into consideration when designing these policies. Quantitatively, we find that achieving net-zero target by 2050 (compared to the laissez-faire scenario) implies a 35.2 percent welfare gain in the long run, while it induces up to a 24.5 percent welfare loss in the short/medium run given a medium-range abatement cost.

In the following, we highlight the four main results, which are related to: i) the impacts of carbon prices on consumption, ii) the role of fiscal redistribution, iii) the interactions between the net-zero transition and inflation, and iv) the role of green innovation.

Our first result is that carbon pricing impacts consumption via wages and rates of return. To achieve this result, we decompose the effect on consumption into direct and indirect effects. (In our framework we only have indirect effects.) In particular, we show how asset returns, wages, profits, and transfers interact to determine the consumption shift following a carbon price shock. While transfers contribute positively to consumption, in contrast,

[1]This isn't precautionary saving in the strict sense of the word, which is often linked to aggregate risk. In our framework households increase their savings to be able to face the expected rise in carbon prices.

wages and asset returns, which are the main drivers, decrease consumption at the aggregate level. As firms face carbon costs, they reallocate resources (capital and labor costs), whereby the shadow input cost[2] decreases, driving both capital returns and labor wages down. We then subject the model results to the case of the California carbon market and find that the model is able to reproduce the same empirical findings. More specifically, in the case of the cap-and-trade market in California, we show that the carbon price shock diffuses through the economy via the energy sector aggregates and then impacts consumers via a drop in wages and asset returns. Using U.S. climate sentiment data provided by Ardia et al. [2020], we construct a climate news instrument. Our high-frequency instrument allows us to capture a wide range of events (e.g. regulatory, disaster, and green technological innovations). We then use the climate news instrument to identify carbon shocks, before using the carbon shocks series in an instrumental variable structural vector auto-regressive framework (IV-SVAR) (Gertler and Karadi [2015], Montiel Olea et al. [2021], and Känzig [2021]) to investigate the aforementioned impacts of carbon pricing on household wages and asset returns.

Our second result addresses the importance of fiscal redistribution in smoothing the distributional impacts both in the short run and over the transition to net-zero by 2050. To this end, we decompose households into different wealth quantiles and income levels. We find that transfers play a major part in smoothing the impact of the carbon price. For instance, we find that an income-based tax rebate best smooths the carbon price shock, as households with a low income level and within the bottom 25 percent wealth quantile—who otherwise most suffer from the carbon tax shock—are able to keep the same level of pre-carbon-shock consumption. Similar to the first exercise, we take the model to the data once again and show how California carbon pricing asymmetrically impacts households, depending on their level of income, and do so by using quarterly consumer survey data. Of particular interest, we find that positive carbon price shocks within the California cap-and-trade market tend to increase the price of energy, which in turn decreases net energy consumption, resulting in lower wages and asset returns. The results are robust to both weak IV bootstrapping and

[2] The marginal cost related to firms' choice of capital return and labor wages.

Cholesky decomposition. In the case of California, the bottom 50 percent income households see their consumption fall, while consumption tends to temporarily increase for the top 50 percent, suggesting unequal consequences of carbon pricing. We conduct a series of sensitivity checks, which indicate that the results are robust along a number of dimensions including the selection of news, the estimation technique, the model specification, and the sample period.

Our third result is that nominal rigidities are an important feature of the net-zero transition. We highlight the linkages between inflation and carbon pricing by considering the case of sticky prices. We show that carbon pricing induces lower inflation over the transition period, while inflationary pressure manifests over the long run, which could represent a challenge for monetary policy conduction in a world with high inflation. This is largely due to the increasing total marginal cost that is driven by higher carbon prices. Although firms decrease their shadow input cost by reallocating capital and labour resources, the rising carbon prices and increasing abatement costs outweigh the decrease in the shadow input cost and thus increase the total marginal cost. As such, inflationary pressures could further deepen the distributional impacts discussed above.

Finally, our fourth result is that green innovation (represented by abatement cost in our framework) plays a major role over the transition and could make the net-zero 2050 emissions target difficult to achieve if cheaper technologies are not developed rapidly. To this extent, we investigate the case of abatement learning and show how fiscal redistribution and green innovation decreases carbon prices and boosts consumption over the transition. With green innovation decreasing abatement investment costs, the impacts on the joint distribution of income and wealth are less pronounced and the net-zero transition is less costly for households and firms alike.

As with the empirical component of our work, we perform a comprehensive series of sensitivity checks, including different calibrations for abatement costs, climate dynamics, climate damages, and policy trajectories.

In addition, we provide a methodological contribution, under which, climate dynamics are cast within the standard incomplete market model pioneered by Imrohoroğlu [1989] and

Aiyagari [1994], in continuous time following Achdou et al. [2022]. Our methodological contributions are twofold. First, we develop a novel and flexible heterogeneous climate macroeconomic framework that accounts for climate dynamics and allows for studying the distributional impacts along the transition to the net-zero emissions target. To this end, we make use of heterogeneous agents models to expand the scope of literature on climate macroeconomics by including household heterogeneity to contribute to the climate mitigation debate. One of our contributions is to integrate the heterogeneous agents climate models into the framework provided by Achdou et al. [2022] and more broadly into the field of "Mean Field Games" (MFG) introduced by Lasry and Lions [2007]. Whereas, a number of climate-macroeconomic empirical studies (e.g. Dell et al. [2012], Burke et al. [2015], Colacito et al. [2018]) and theoretical work such as Rudik et al. [2021] focus on heterogeneity of climate damages, we, on the other hand, focus on household heterogeneity in terms of income/wealth, and are able to contrast the distributional impacts of the net-zero transition between the short/medium run and the long run, impacts that are not due to environmental preferences or heterogeneous climate modeling choices. Second, we show how the long-run steady states of the economy are solved under the presence of climate dynamics, as well as how transition dynamics are computed following the seminal work of Achdou et al. [2022]. Moreover, we highlight that under the presence of nominal rigidities, relying on the system of equations method to solve the transition dynamics for the marginal cost is necessary, as the updating iterative algorithm rule does not allow for convergence when used to clear the New Phillips Curve.

Literature Review. Where an extensive part of the literature focuses on the optimal price of carbon, also referred to as the social cost of carbon 'SCC' (Nordhaus [1991], Stern [2008], Weitzman [2012], and Dietz and Stern [2015], among many others), the macroeconomic impacts of reaching net-zero emissions have received far less attention. These papers focus on the level of the optimal cost of carbon in a representative agent model, where the goal is to characterize the price level needed to offset carbon emissions. The uncertainty, however, around the optimal price (Cai and Lontzek [2019], Van der Ploeg et al. [2020], Barnett et al. [2020], and Traeger [2021]) suggests difficulties regarding its implementation. In a recent paper, Benmir and Roman [2020] investigate the consequences of net-zero emissions targets in the context of the EU. They show that following an optimal policy is not sufficient, and, therefore, there is a need for sub-optimal policy (such as the European Trading System (ETS)) to reach the net-zero target. This sub-optimal price level induces welfare losses at the aggregate level and could dissimulate disparities at the household level, suggesting potential negative impacts on the distribution. However, none of these papers clearly identify the transition dynamics and its impacts over the distribution using a fully heterogeneous agent model.

Another major part of the the literature focuses on the role of technological change and innovation in climate change mitigation (e.g. Smulders and De Nooij [2003], Grimaud and Rouge [2008], Di Maria and Valente [2008], Acemoglu et al. [2012], Aghion et al. [2016], and Acemoglu et al. [2019]), where household heterogeneity is often overlooked. While these papers shed light on the role of technology over the transition, they do not capture the potential trade-off between: i) using carbon pricing revenue to steer green innovation, and ii) smoothing the potential distributional costs linked to setting a carbon price.

However, recently, building on Bosetti and Maffezzoli [2013], who were the first to show the importance of accounting for heterogeneity (in household income) when investigating climate policy interaction with macroeconomic aggregates, Cavalcanti et al. [2021] study the distributional effects of climate change mitigation policies within and across countries. Similarly, Malafry and Brinca [2022] assess how household heterogeneity implies different levels of carbon price preferences. They, however, do not investigate the transition dynamics with a joint household income/wealth distribution and endogenous energy sector where energy prices are subject to demand and supply markets. Furthermore, Fried et al. [2018] and Fried et al. [2021] use a heterogeneous life-cycle model to investigate the impact of carbon taxes on future generations, while Goulder et al. [2019] use a computable general equilibrium model to assess the carbon tax's negative distributional impacts. In addition, Bakkensen and Barrage [2021] investigate the impact of belief heterogeneity on coastal housing markets, using a dynamic model. We contribute to this literature by providing a framework: i) that allows for transition pathways, where energy is an endogenous input to other sectors of economy; ii) that encompasses full climate dynamics; and iii) that captures full household heterogeneity (in income and wealth); all of which, we argue are essential components for understanding the full scope of the impacts of the net-zero emissions target.

These largely theoretical studies contrast with a number of empirical findings by, for example, Metcalf [2019], Shapiro and Metcalf [2021], and Bernard and Kichian [2021], who find no significant effect of carbon policy on macroeconomic aggregates. Our work bolsters the findings of Känzig [2021], who in contrast to the aforementioned empirical papers, find a significant and negative impact of carbon pricing on macroeconomic aggregates. Similar to Känzig [2021], others, such as Mansanet-Bataller and Pardo [2009], and Bushnell et al. [2013], also use event study methodology to investigate the impacts of regulatory carbon and energy news on prices. We contribute to this growing literature by employing the Sentometrics index developed by Ardia et al. [2020] in our study of the California cap-and-trade carbon market.

While the heterogeneous macroeconomic literature proposes a set of methods (e.g. Ahn et al. [2018] and Auclert [2019]) to solve dynamic systems, we follow Achdou et al. [2022] and use the finite difference method developed by the authors for solving our heterogeneous agent model and for computing the Hamilton-Jacobi-Bellman (HJB) as well as for the Kolmogorov Forward equations. As the main focus of our paper is the net-zero distributional impacts, we rely on MIT shocks and do not focus on aggregate risk (Den Haan [1997], Krusell and Smith [1998], Reiter [2009], Boppart et al. [2018], and Auclert et al. [2021], among others) in this paper.

For practical purposes, we will first present the empirical findings and then move to the theoretical results, which are the core of the paper. Our empirical results are to be considered in light of the theoretical model's numerical exercises. The empirical exercises serve to ensure that the results of the theoretical model are consistent with the carbon pricing propagation channels for the case of California, which is an imperfect but available representation of what could happen at the U.S. level and is the only large carbon market in the country.

Section 2 presents our empirical findings, while section 3 outlines our continuous-time climate macroeconomic model of income and wealth distribution. Section 4 describes our computational algorithm for both stationary and time-varying equilibria. Section 5 delineates our net-zero transition quantitative results. Section 6 highlights the impacts of net-zero on inflation. Section 7 presents the case of learning by doing. Section 8 concludes.

2 Empirical Analysis

As the main objective of our paper is to investigate the net-zero distributional impacts on households, understanding the channels through which carbon pricing propagates in the economy is paramount. Our empirical study on the California cap-and-trade market sheds some light on the ways by which carbon pricing impacts aggregate prices and different consumers. We then use the empirical findings to discipline our theoretical framework and ensure consistency of the channels through which carbon pricing impacts the economy at large and households more specifically.

While our main study looks at U.S. net-zero distributional impacts, our choice of the California carbon market is due to the absence of a generalized carbon market in the U.S. (as is the case for the European Union). We, therefore, use California as a proxy for the U.S. in terms of potential propagation channels when setting a carbon price.

To conduct our empirical analysis, we make use of the event studies found in the monetary literature (e.g. Kuttner [2001], Gertler and Karadi [2015], and Nakamura and Steinsson [2018]) that use news shock strategies to identify structural shock instruments, which we then couple with a climate "Sentometric" index (Ardia et al. [2020]) that summarizes the climate sentiment (i.e. whether media report positive or negative news about climate change) at a daily frequency in the U.S.

2.1 The California Market at a Glance

The California carbon cap-and-trade program is considered to be one of the largest[3] multi-sectoral emissions trading systems in the world, along with the EU ETS.

The program aims at a reduction of emissions by 40 percent below 1990 levels by 2030, and has a goal of reaching carbon neutrality by 2045, which is a far more ambitious goal than the U.S. net-zero recent pledges (carbon neutrality by 2050). California's program covers GHG sources responsible for approximately 85 percent of the state's CO_2 emissions. It relies on two types of compliance instruments: i) allowances and ii) offsets, which are traded on secondary markets (spot and futures markets).

Revenue from carbon pricing, which the regulator has amassed, comes to 5 billion dollars of total revenue since the beginning of the program. The total revenue is used, on one hand, for a Greenhouse Gas Reduction Fund (65 percent) to help implement programs aiming at further reducing CO_2 emissions, and, on the other hand, as a redistribution tool for environmentally disadvantaged and low-income communities (35 percent).

In the following section, we investigate the linkages between the California cap-and-trade system and different macroeconomic prices and aggregates.

2.2 The Carbon Policy Instrument

Building on the event study literature, we use the comprehensive Sentometric index[4] by Ardia et al. [2020], which lists all daily news on climate sentiment in the U.S. from 2003 to 2018. We then take the mean over the period of interest (2012 to 2018) and only consider a news shock to be the days where a higher level of climate news was observed compared to the mean. This reflects a movement in the sentiment and/or the regulatory constraints, which we use as an event news shock to the California carbon price. As the selection of events is a fundamental factor in event studies, we run a sensitivity analysis with different thresholds to control for possible confounding noise in the data.

[3] It is the fourth largest in the world, following the cap-and-trade programs of China, the European Union, and the Republic of Korea.

[4] All index data are publicly shared by the authors: https://sentometrics-research.com/download/mccc/.

Sentometric index data are provided daily, which allows us to perform a high-frequency analysis when constructing the carbon policy surprise series. Following Gertler and Karadi [2015], we construct the carbon surprise series (τ_t^{Shock}) as the change of carbon prices (τ_t^{C}) between the event day[5] and the previous day as follows:

$$\tau_t^{\text{Shock}} = \begin{cases} \tau_t^C - \tau_{t-1}^C & \text{If } \text{day}_t(\text{Carbon Index}) \geq \frac{1}{T}\sum_{i=1}^{T} \text{Carbon Index}_i, \\ 0 & \text{otherwise.} \end{cases} \tag{1}$$

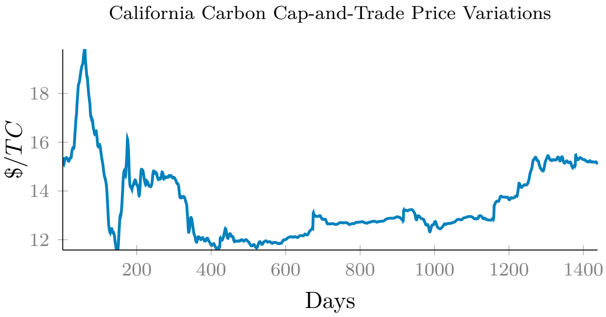
A question that is usually of concern is the reverse causality. In our framework, we are less subject to it as our measure of the price change is at a sufficiently high frequency (daily news), which allows us to isolate the impact of the news sentiment confidently.

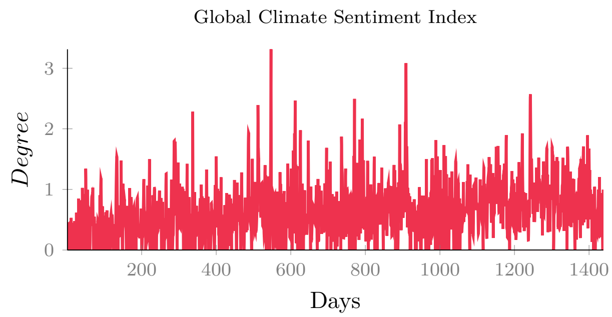
Furthermore, although we construct our carbon surprise series at a daily frequency, we aggregate all data to a monthly level in order to fit with the other macro-aggregate data, which are only available at a monthly frequency. In order to study the macroeconomic impact of carbon policy we rely on four aggregates, namely: i) energy composite price, ii) energy net generation, iii) weekly wages of the energy and utilities sector, iv) returns on equity index, which are all taken at a monthly frequency (or aggregated to monthly for the returns on equity index and energy prices), all for the state of California.[6] The sample spans the period from April 2012 to April 2018, a period for which we have available data on climate sentiment as well as for all the other variables.

[5] Where we use front contract on carbon allowances futures.

[6] For details on data sources, please refer to Appendix A.

FIGURE I. Carbon Prices and Climate Index





Note: The left figure displays the CO_2 future prices for the California cap-and-trade market between the 1st of May 2011 and the 27th of March 2018 at a daily frequency. The figure on the right, shows the climate sentiment index for the same period.

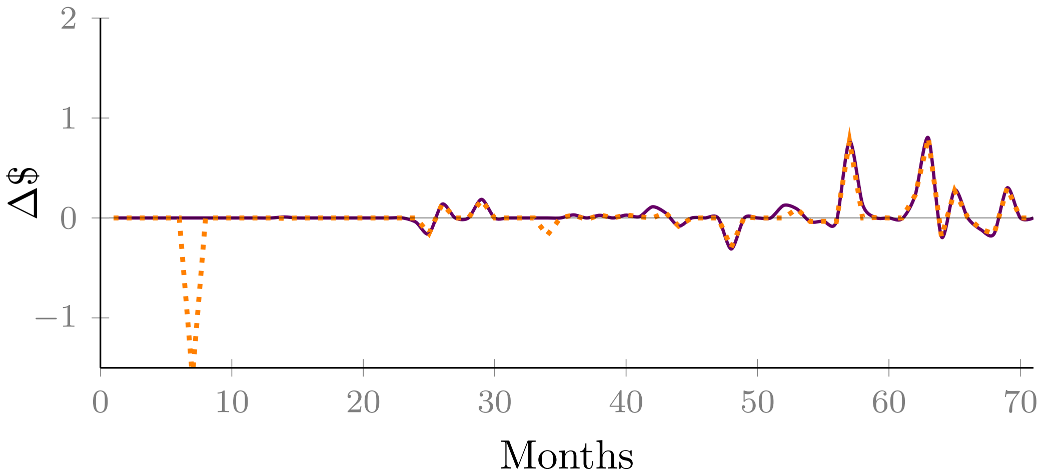
To illustrate the data used to extract the policy instrument in figure II, we present the carbon price and climate sentiment index in figure I. Relying then on the strategy outlined above, we show the carbon policy surprise series for two cases: i) where we include all days with zero news on climate, and ii) where we exclude all days with zero news on climate. A 'zero' news day means that either we have no information or that sentiment over climate change is positive.[7] Excluding these zero news days shifts the mean of the sentiment around climate change, which shifts movements over the policy price shock.

We can see that excluding days with no or zero news adds more variation (orange dotted line) compared to our baseline case where we consider that the days with zero news are days with positive sentiment over climate change.[8]

[7] What is meant by positive, is a lack of negative news on climate change.

[8] In figure XXVI and figure XXV we show that our results remain strong to this hypothesis.

FIGURE II. Carbon Price Policy Instrument



Note: The figure presents the shock to futures contract carbon prices (price difference for relevant days) for the California carbon market used as an external instrument in our study. We use the climate index daily data to extract the shock from the carbon prices, which then we aggregate to monthly levels. Data are presented at a monthly frequency for the period between the 1st of May 2011 and the 27th of March 2018. In dotted orange we present the case where the aggregation of climate news events excludes all 'zeros' (i.e. days without any climate news). Whereas, the purple solid line presents the aggregation of climate news events events where we includes all zero news days.

2.3 Validity of the Carbon Policy Instrument

Following both Ramey [2016] and Montiel Olea et al. [2021], we first investigate the auto-correlation function and verify that our policy instrument is not explained by our macroeconomic aggregate series. We do this by conducting a Granger causality test. We find no auto-correlation (p-value of Q-stat for H0 is 0.99) and no significance of the Granger causality test.

2.4 Impacts of Carbon Price Policy on Aggregate Macro-Variables: IV-SVAR Model

While in our framework, we could use the constructed carbon policy surprise series as a direct measure of our shock of interest,[9] we allow for some errors in our policy surprise series, and thus use it as an instrument instead of a direct policy shock.

We use an SVAR to derive the impulse responses of the variables of interest following our carbon policy shock. To set our VAR, we follow Montiel Olea et al. [2021].

[9] We do that as robustness check, and find similar results. Please refer to Appendix A.

Let Y_t be a 4 x 1 vector of observables (energy prices, net energy generation, wages, equity index returns). We assume that the dynamics of the observables are described by a system of linear simultaneous equations:

$$Y_t = \sum_{j=1}^{p} A_j Y_{t-j} + \eta_t, \tag{2}$$

where η_t is a vector of reduced-form VAR innovations. We can re-write the reduced form innovations as a vector of structural shocks ϵ_t:

$$\eta_t = \Gamma \epsilon_t, \tag{3}$$

where Γ is a non-singular 4 x 4 matrix.

The method relies on two main assumptions: i) the invertability of the structural VAR (i.e. VAR forecast errors at date t are a non-singular transformation of the structural errors at date t) and ii) the structural shocks are assumed to be serially and mutually uncorrelated:

$$E(\epsilon_t) = 0, \tag{4}$$

$$E(\epsilon_t \epsilon_t') = diag(\sigma_1^2, ..., \sigma_n^2). \tag{5}$$

Therefore, the covariance matrix for the reduced form innovations reads as:

$$E(\eta_t \eta_t') = \Sigma = \Gamma diag(\sigma_1^2, ..., \sigma_n^2) \Gamma', \tag{6}$$

In our research question, we are interested in the causal impact of the carbon policy shock on the set of observables. In other words, we are interested in the structural impulse response coefficient. In our framework this is the response of our observables to a one unit change in the policy shock, which we denote as $\epsilon_{1,t}$:

$$\frac{\partial Y_{i,t+k}}{\partial \epsilon_{1.t}} = e_1' C_k(A) \Gamma e_1, \tag{7}$$

where C_k corresponds to the Wold decomposition of the VAR and emphasizes the dependence of the MA coefficients on the AR structure coefficients in A, and e_1 is the first column of the identity matrix.

Since we use the carbon policy as an instrument—which we denote as z_t—instead of a direct measure,[10]), we require both the relevance and the exogeneity conditions to hold:

$$E(z_t \epsilon_{1,t}) = \alpha \neq 0, \tag{8}$$

$$E(z_t \epsilon_{j,t}) = 0 \text{ for } j \neq 0. \tag{9}$$

Having outlined the instrumental variable SVAR framework, we estimate the impulse responses function coefficients for the VAR in levels (Sims et al. [1990]) where all variables are taken in logs, using a Two-Stage Least Squares (2SLS) methodology. We conduct the 2SLS using our instrument z_t and regressing $\hat{\eta}_t$ on $\hat{\eta}_{1,t}$. We rely on the bootstrap residual moving block as in Montiel Olea et al. [2021].

Furthermore, we use eight lags in our SVAR as suggested by the AIC criterion. We also allow for twelve lags on the Newey-West standard errors in order to capture possible auto-correlation within our monthly data.

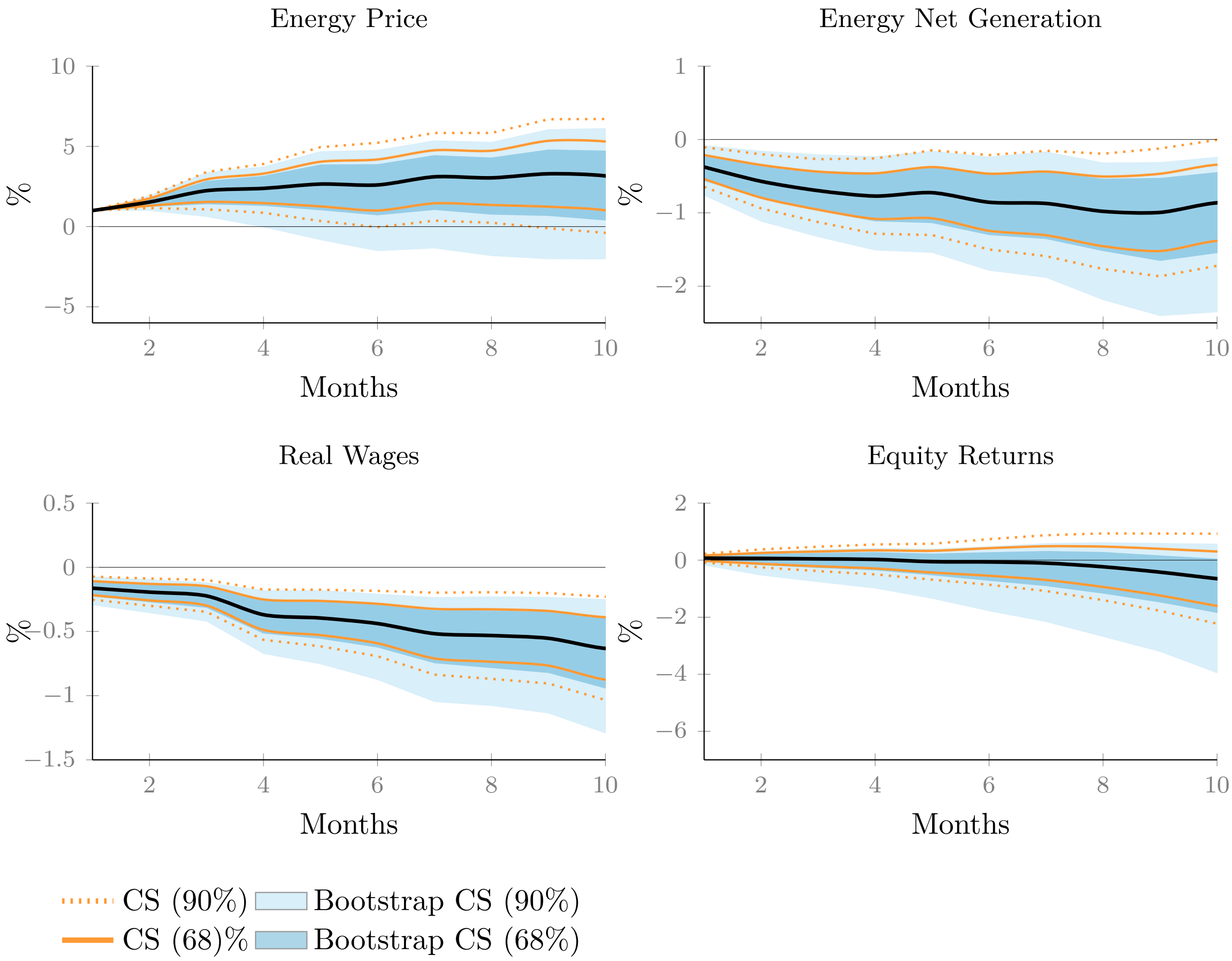
Finally, we conduct both standard inference and weak IV inference as suggested by Montiel Olea et al. [2021], since the heteroskedasticity robust F-statistic in the first stage of the IV-SVAR is less than the critical value of ten but higher than four.

2.5 Impacts of Carbon Price Policy on Aggregate Macro-Variables: Results

Turning to the results of our IV-SVAR model, Figure III presents the standard inference results. More precisely, it shows the impulse responses (IRFs) to the identified carbon policy shock, normalized to increase the energy price by one percent on impact. The solid black lines represent the estimated paths. The shaded blue areas are the 68 and 90 percent confidence bands, while the orange solid and dotted lines are the 68 and 90 percent confidence bands computed using the bootstrapping procedure.

[10] In the Appendix A we show the impulse responses when the policy shock is used as a direct measure in the SVAR.

FIGURE III. IV-SVAR



Note: The figure presents the cumulative impulse responses to California carbon price market shocks, where we normalize the impact of the carbon shock to one percent on impact. In blue, we show the 68 and 90 percent confidence bands, while in orange we present the 68 and 90 percent confidence bands using bootstrapping procedure. In this exercise, the carbon shock is constructed excluding including all days with zero or no news.

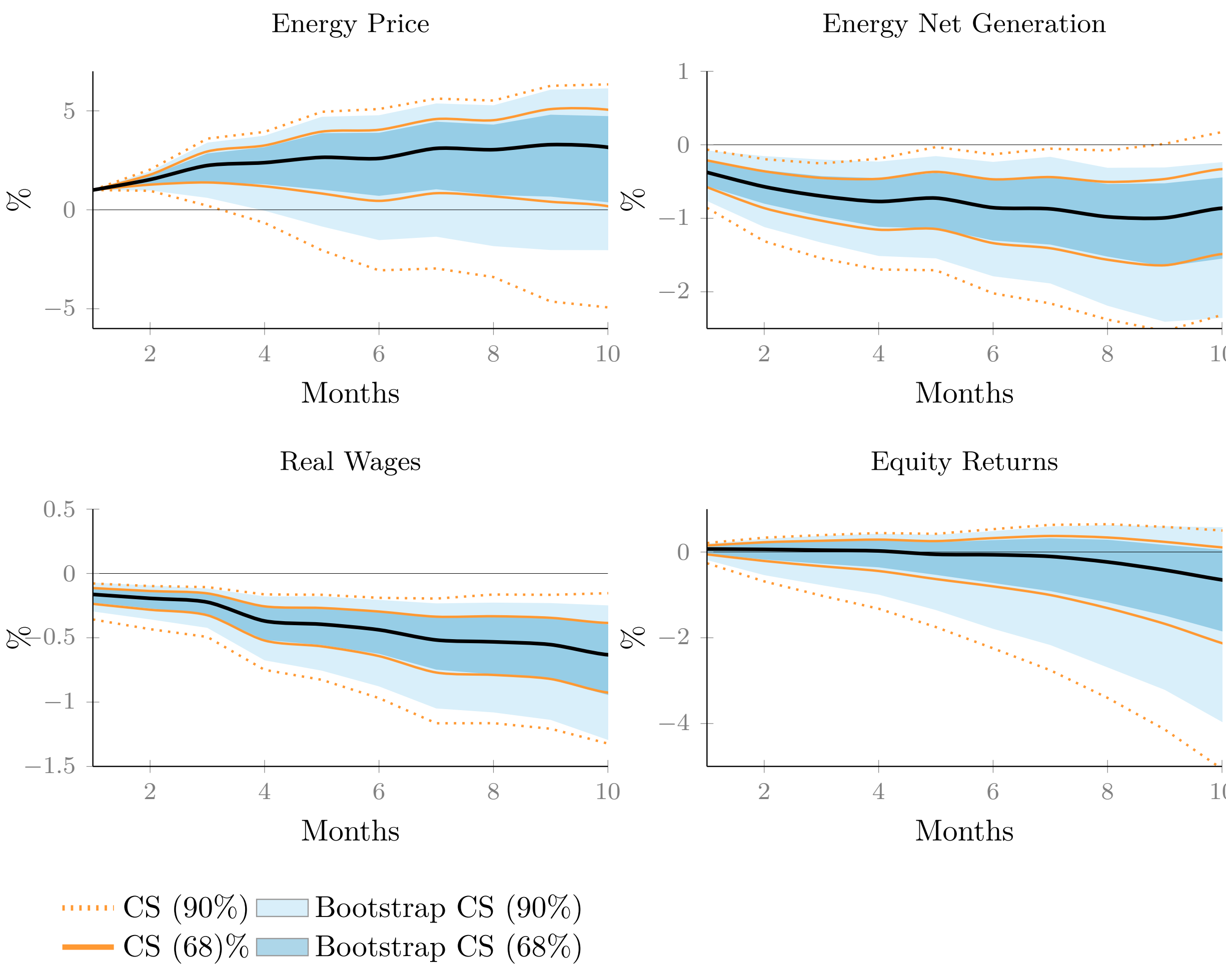
Results show that a carbon policy shock leads to a persistent increase in energy prices, which triggers a persistent decrease in net energy generation. This rise in energy price and fall in energy generation induce a cost to firms and consumers. As firms input costs increase with higher carbon prices, they engage in resource reallocation, which leads to a persistent decrease in wages. With respect to equity returns, the fall does not manifest immediately, but is observed seven periods following the shock.

From both a statistical and economic perspective, the results are significant. As shown by the confidence intervals, the directions of the effects are clearly identified. In terms of magnitudes, the results are also economically significant. A carbon policy shock increasing energy prices by 1 percent leads to a 1 percent decrease in net energy generation and to about 0.6 percent decrease in wages paid to employees of the energy and utilities sector, whereas returns on equity fall by about 2 percent by the end of the 15 months period.

When relying on the weak IV inference, the results turn out to be robust and similar in terms of magnitude, direction, and statistical significance, as shown in Figure IV. Finally, the results from both: i) the instrument where we exclude zero day news and ii) the standard Cholesky SVAR (where we use the external instrument as a direct internal variable),[11] turn out to be very similar, which supports our overall results.

[11] Refer to appendix A for more details.

FIGURE IV. Weak IV-SVAR



Note: The figure presents the cumulative impulse responses to California carbon price market shocks, where we normalize the impact of the carbon shock to one percent on impact. In blue, we show the 68 and 90 percent confidence bands, while in orange we present the 68 and 90 percent confidence bands using bootstrapping procedure. In this exercise, the carbon shock is constructed excluding including all days with zero or no news. The inference is conducted using weak IV robust bootstrapping procedure.

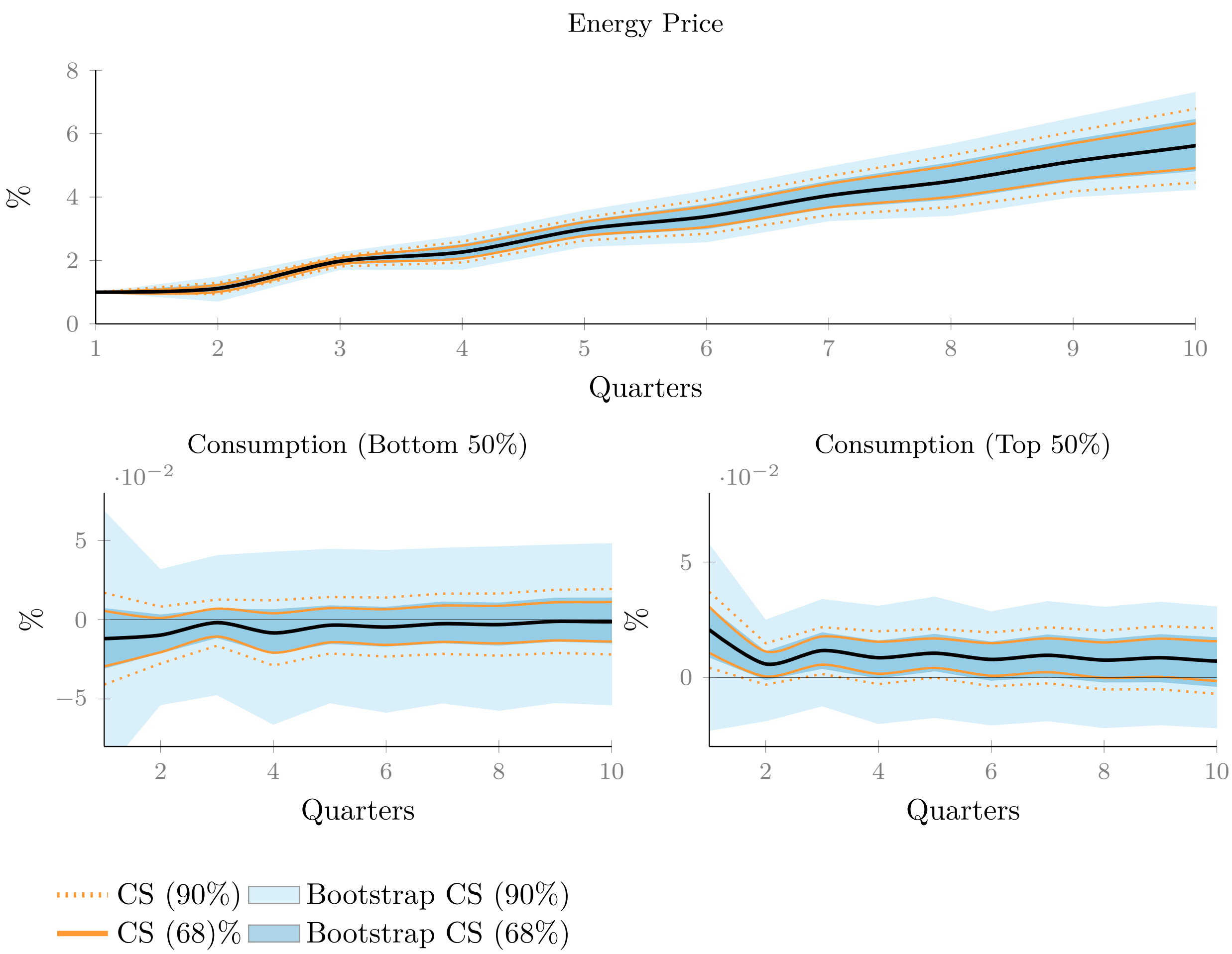
2.6 The Impacts of Energy Prices on Consumption Quantiles: SVAR

As the main focus of this paper is to investigate the heterogeneous impacts of carbon pricing on households, we use the quarterly Consumer Expenditure Surveys (CES), which provide detailed data on household consumption baskets and income levels. The CES provide data on locations of participants, so we focus on California (as it is the main carbon market in the U.S.) and expand the data to five years prior to the first future carbon contracts in order to have sufficient data points to conduct our inferences (Q1-2006 to Q4-2019). The instrument values are set to zero for all quarters prior to 2012 (the time at which futures carbon contracts are available) as argued by Känzig [2021]. We follow the same methodology as in the previous section to construct our carbon instrument, with the only difference being that we aggregate Sentometric climate news over quarters and not months for this exercise.

Figure V presents the standard inference results. More precisely, it shows the impulse responses (IRFs) to the identified carbon policy shock, normalized to increase the energy price by one percent on impact. The solid black lines represent the estimated paths. The shaded blue areas are the 68 and 90 percent confidence bands, while the orange solid and dotted lines are the 68 and 90 percent confidence bands using bootstrapping procedures as was the case for the first IV-SVAR model presented above. The standard errors are computed with Newey-West four lags to account for potential auto-correlation within quarters. We also include two lags in the VAR.[12]

[12] The results are robust even when we include 4 lags.

FIGURE V. IV-SVAR Consumption Qunatiles



Note: The figure presents the cumulative impulse responses of bottom 50 percent income household versus top 50 percent income household located in California to California carbon price market shocks, where we normalize the impact of the carbon shock to one percent on impact. In blue, we show the 68 and 90 percent confidence bands, while in orange we present the 68 and 90 percent confidence bands using bootstrapping procedure. In this exercise, the carbon shock is constructed excluding including all days with zero or no news. The inference is conducted using robust bootstrapping procedure. We conduct to IV-SVAR separate regressions for each income quantile.

Results show that a carbon policy shock leads to a persistent increase in energy prices, which triggers an asymmetric consumption reaction. The bottom 50 percent income households see their consumption fall, while the top 50 percent income households experience a rise in their consumption before it falls back to its steady state level.

Both from a statistical and economic perspective, the results are significant (at 68 percent). As shown by the confidence intervals, the directions of the effects are clearly identified. Two main reasons could explain the small magnitude of the results. First, California recycles its revenues from carbon pricing and redistributes a part of it (35 percent) to low income households, which could smooth the carbon price shocks transmitted via the energy price increase. However, as we do not have access to such fiscal data, we cannot control for the impacts of the redistribution. Second, to conduct our inference, we included a period of five years where there was no carbon pricing market in place. As mentioned above, the instrument values are set to zero for all quarters prior to 2012. Under such a framework, the carbon price instrument contains multiple zeros, which could result in biasing estimates downward.

3 The Theoretical Model

Building on Golosov et al. [2014], Dietz and Venmans [2019] and Achdou et al. [2022], we develop a heterogeneous agent climate model with two production sectors. Accordingly, where McKay et al. [2016] and Kaplan et al. [2018], among others, rely on *MIT shocks* to analyze the responses of the economy to a monetary shock. We use the same methodology to investigate a carbon price shock as environmental authorities plan far-ahead changes to their tax regulations and/or emission cap system and leave little space for uncertainty.

The modeled economy is characterized by continuous-time and an infinite horizon and is comprised of two types of *firms (energy producers and non-energy producers)*,[13] *heterogeneous households*, and a *government*. In this setup, production by firms induces an environmental externality through CO_2 emissions. A damage function relates rising emissions generated by firms' production to a deterioration in global productivity.

We first present the climate dynamics of our economy, and then present the energy firms followed by an explication of the non-energy firms' intermediate and final goods. We thereafter present the household problem, and the government policy framework.

[13]Both type of firms are infinitely lived and of measure one.

3.1 Climate Dynamics

As highlighted in the standard integrated assessment models (IAMs) (see Nordhaus [1991]), a large part of the accumulation of CO_2 and other Greenhouse Gases (GHGs) in the atmosphere results from the human activity of economic production. Following recent work by Dietz and Venmans [2019], we describe the concentration process of Carbon Dioxide X_t in the atmosphere as follows:

$$\dot{X}_t = E_t + E_t^{Row}, \tag{10}$$

where $X_{2020} = 840$ is the initial value of emissions stock in GTons of CO_2 and $E_t \geq 0$ is the inflow of Greenhouse Gases at time t, and E_t^{Row} is the inflow of the rest of the world's emissions.[14]

The total level of emissions flow is a sum of all emissions of its j firms of its s sectors:

$$E_t = \sum_s E_t^s = \sum_s \int_0^1 e_{j,t}^s dj, \tag{11}$$

with $e_{j,t}^s$ being the emissions flow of firm j of sector s. In our framework, the total emissions flow reads as:

$$E_t = E_t^y + E_t^e = \int_0^1 e_{j,t}^y dj + \int_0^1 e_{j,t}^e dj, \tag{12}$$

where $e_{j,t}^y$ are emissions from non-energy firms and $e_{j,t}^e$ are emissions from energy firms.

In addition, we define the relationship between the temperature vector T_t^o and the stock of emissions in the atmosphere X_t as follows:[15]

$$\dot{T}_t^o = \phi_1(\phi_2 X_t - T_t^o), \tag{13}$$

with ϕ_1 and ϕ_2 representing the climate sensitivity parameters.

The impact of global warming on the economy is reflected by a convex damage function

[14] E_t^{Row} is assumed to evolve similarly to domestic emissions. This assumption implies international cooperation and is important to achieve the climate target of staying below 2C degrees.

[15] In our setup T_t^o represents the atmospheric temperature level. As a robustness exercise we model the climate following the three boxes framework as in Cai and Lontzek [2019] (please refer to Appendix B for more details). The results remain similar to the Dietz and Venmans [2019] specification.

of temperature in the atmosphere. This is a standard feature of the IAMs family:

$$d(T_t^o) = ae^{-b(T_t^o)^2}, \tag{14}$$

with a and b the two parameters shaping climate damages.

3.2 Non-Energy Firms

The non-energy production sector is comprised of final and intermediate firms. We first present the final before turning to the intermediate firms.

3.2.1 The Final Firms

Our representative final firms produce a final good Y_t in a competitive sector, which is an aggregate of intermediate firms output $y_{j,t}$ (where $j \in (0,1)$ is the continuum of intermediate firms):

$$Y_t = \int_0^1 \left(y_{j,t}^{1-\frac{1}{\theta}} \right)^{\frac{1}{1-\frac{1}{\theta}}}, \tag{15}$$

where $\theta \in (1, \infty)$ is the elasticity of substitution between the intermediate goods. Final firms in the model are looking for profit maximization (in nominal terms), at a given price P_t, subject to the intermediate goods j prices $p_{j,t}$. The first order condition for the final firm profit maximization problem yields:

$$y_{j,t} = \left(\frac{p_{j,t}}{P_t} \right)^{-\theta} Y_t. \tag{16}$$

Under perfect competition and free entry, the price of the final good denoted as P_t is expressed with respect to the intermediate firm price $p_{j,t}$:

$$P_t = \left(\int_0^1 p_{j,t}^{1-\theta} dj \right)^{\frac{1}{1-\theta}}. \tag{17}$$

3.2.2 Intermediate Firms and Environmental Externality

Our intermediate representative firm j produces goods using a standard Cobb-Douglas function with climate damages. It seeks profit maximization by making a trade-off between, on one hand, the desired level of capital, labor, and energy, subject to climate damages, and on the other hand, the price of energy paid to energy producers, capital and abatement investment, as well as the cost implied by the environmental policy paid to the regulator. The production function reads as:

$$y_{j,t} = A_t d(T_t^o) {k_{j,t}^y}^{\alpha_1} {e_{j,t}^n}^{\alpha_2} {l_{j,t}^y}^{1-\alpha_1-\alpha_2}, \tag{18}$$

where α_1 and α_2 are the elasticities of output with respect to capital $k_{j,t}^y$ and energy e^n, A_t is the TFP,[16] $k_{j,t}^y$ the capital used by intermediate firms, $e_{j,t}^n$ the level of energy demand, and $l_{j,t}^y$ the effective units of labour input. In our framework, firms' productivity is subject to climate dynamics. As in the real business cycle model presented in Golosov et al. [2014], the environmental externality constrains the Cobb-Douglas production function of the firms, where the emissions feedback deteriorates the environment and alters the production possibilities for firms. However, we differ from Golosov et al. [2014] by incorporating damages from the stock of emissions through the level of temperature as outlined in subsection 3.1.

Economic production results in emission flows of CO_2, which is modeled as follows:

$$e_{j,t}^y = \left(1 - \mu_{j,t}^y\right) \varphi_t^y y_{j,t}, \tag{19}$$

where $e_{j,t}^y$ represents the emissions flow generated by firm j, and $0 \leq \mu_{j,t}^y \leq 1$ the fraction of emissions abated by firms.

This functional form for emissions allows us to take into account the high-frequency variations in CO_2 emissions. The term φ_t^y denotes the total inflow of emissions resulting from production, prior to abatement. In this expression, $\varphi_t^y = \bar{\varphi}^y \Omega_t$ with $\bar{\varphi}^y$ being the carbon-intensity parameter that pins down the steady-state ratio of emissions-to-output, while Ω_t represents a trend in the emissions intensity, which captures the decoupling of emissions to output that results from technological improvements.

Furthermore, intermediate firm j incurs a cost $F(\mu_{j,t})$ for every emission unit abated, where $\mu_{j,t}$ is the abatement level. Following Nordhaus [2008], abatement costs read as

[16] In the context of the net-zero quantitative simulations, $A_t = \gamma A_{t-1}$ where γ is the exogenous growth rate of the economy.

follows:

$$F(\mu_{j,t}^{y}) = f(\mu_{j,t}^{y})y_{j,t}, \tag{20}$$

where

$$f(\mu_{j,t}^{y}) = \theta_1 {\mu_{j,t}^{y}}^{\theta_2},\ \theta_1 > 0,\ \theta_2 > 1, \tag{21}$$

with θ_1 and θ_2 shaping the cost of abatement for the non-energy sector.

The profits of the representative intermediate firm $\Pi_{j,t}^{F}$ will thus be impacted by the presence of the environmental externality. As the firm do not internalize its impacts, the regulator then imposes an environmental policy, which forces the firm to engage in abatement efforts, as otherwise it would pay a carbon price to the regulator with respect to its emissions level. The revenue is the real value of intermediate goods $y_{j,t}$, while the cost arises from the following: energy needed $e_{j,t}^{n}$ in the production cycle, the capital investment level $i_{j,t}^{y}$, wages w_t^{y} paid to the labor force $l_{j,t}^{y}$, abatement effort $\mu_{j,t}^{y}$, and the environmental carbon price τ_t^{y}. The profit equation reads as:

$$\begin{aligned} \Pi_{j,t}^{F} &= \frac{p_{j,t}}{P_t} y_{j,t} - w_t^{y} l_{j,t}^{y} - i_{j,t}^{y} - p_t^{e} e_{j,t}^{n} - f(\mu_{j,t}^{y}) y_{j,t} - \tau_t^{y} e_t^{y} \\ &= \left(\frac{p_{j,t}}{p_t} - mc_{j,t} \right) y_{j,t}, \end{aligned} \tag{22}$$

subject to,

$$\dot{k}_{j,t}^{y} = i_{j,t}^{y} - \delta k_{j,t}^{y}, \tag{23}$$

$$y_{j,t} = A_t d(T_t^{o}) {k_{j,t}^{y}}^{\alpha_1} {e_{j,t}^{n}}^{\alpha_2} {l_{j,t}^{y}}^{1-\alpha_1-\alpha_2}, \tag{24}$$

with p_t^{e} the price paid to the energy firms for energy supplied.

Given a price, and subject to the demand constraint, the cost-minimization problem yields the real marginal cost, which can be expressed following the first-order conditions with respect to the firm's optimal choice of energy, capital investment, labour, and abatement investment, respectively:

$$p_t^e = \varrho_t^y \alpha_2 \frac{y_t}{e_t^n}, \tag{25}$$

$$r_t^y = \varrho_t^y \alpha_1 \frac{y_t}{k_t^y} - \delta, \tag{26}$$

$$w_t^y = \varrho_t^y (1 - \alpha_1 - \alpha_2) \frac{y_t}{l_t^y}, \tag{27}$$

$$\tau_t^y = \frac{f(\mu_t^y)'}{\varphi_t^y}, \tag{28}$$

where $\varrho_{j,t}^y = \varrho_t^y$ is the marginal cost component related to the same capital demand all firms choose. This price component is common to all intermediate firms as they are identical.

Equation (28) is the optimal condition on abatement: abating CO_2 emissions is optimal when its marginal gain equals its marginal cost. As in Benmir and Roman [2020], this equation highlights the key role of the carbon price in shaping firms' decisions. In addition, abatement efforts μ_t^y are common to all firms of the same sector, as the environmental cost is also common to all firms of the same sector. Furthermore, as the impact of the environmental externality is not internalized by firms (i.e. they take X_t and T_t^o as given), the shadow value of the environmental externality is zero under the laissez-faire. This means firms will have no incentive to engage in abatement effort and emission reduction.

In addition, we can express the total marginal cost as the sum of input cost, abatement cost, and net abatement carbon price:

$$mc_{j,t} = mc_t = \varrho_t^y + f(\mu_t^y) + \varphi_t^y \tau_t^y (1 - \mu_t^y), \tag{29}$$

When prices are flexible (i.e monetary neutrality),[17], the only distortion in our framework arises from monopolistic competition. Using equation (22) as well as equation (16), we can

[17] In section 6 we investigate the case where prices are sticky (i.e. the New Keynesian Heterogeneous Agent framework–HANK).

write the marginal cost and firm's profit as follows:[18]

$$mc_t = \frac{\theta - 1}{\theta}, \tag{30}$$

$$\Pi_t^F = (1 - mc_t)Y_t. \tag{31}$$

3.3 The Energy Producers

Energy producers provide energy resources $e_{j,t}^n$ to the intermediate firms $y_{j,y}$ by relying on physical capital $k_{j,t}^n$, and labour $l_{j,t}^n$. They produce energy using a Cobb-Douglas production function:

$$e_{j,t}^n = A_t^n k_{j,t}^{n\ \alpha_n} l_{j,t}^{n\ 1-\alpha_n}, \tag{32}$$

with α_n the elasticity of energy production to capital $k_{j,t}^n$, and $l_{j,t}^n$ the fraction of labour used by the energy sector.

Producing energy generates a level of emissions, which if not abated (i.e. made greener), is costly for the energy producers. The emissions level is modeled by a nonlinear technology similar to the one used by the intermediate non-energy firms that allows for reducing the inflow of emissions. The emission flow of CO_2 from energy producers ($e_{j,t}^e$) reads as:

$$e_{j,t}^e = \left(1 - \mu_{j,t}^n\right) \varphi_t^n e_{j,t}^n. \tag{33}$$

As is the case for the intermediate firms, $0 \leq \mu_t^n \leq 1$ is the fraction of emissions abated by energy firms. The energy firm will face an abatement investment technology similar to the non-energy firms $F(\mu_{j,t}^n) = \theta_1 \mu_{j,t}^{n\ \theta_2}$ for every emission unit abated,[19] where $\mu_{j,t}^n$ is the abatement level of the energy firm. φ_t^n is the carbon-intensity function for the energy sector and follows a similar law of motion as the non-energy firms. Similarly, the trend in the carbon-intensity process of non-energy firms allows us to match the empirical sectoral decoupling in the U.S.

Again, similar to non-energy firms, the profits of the representative energy firm $\Pi_{j,t}^E$ will

[18] Refer to appendix section C.2 for full derivations.

[19] We assume both sectors use the same abatement technology (i.e. the same abatement cost function). While abatement cost functions are assumed to be the same across sectors, the total abatement cost will be different across the two sectors.

be impacted by the presence of the environmental policy. In this case, revenues are the real value of energy production $e^n_{j,t}$, while the costs arise from investment $i^n_{j,t}$ in physical capital $k^n_{j,t}$, wages w^n_t paid to the labor force $l^n_{j,t}$, and the abatement investment $\mu^n_{j,t}$, as well as the environmental carbon price τ^n_t. The profit equation reads as:

$$\Pi^E_{j,t} = p^e_t e^n_{j,t} - w^n_t l^n_{j,t} - i^n_{j,t} - f(\mu^n_{j,t}) e^n_{j,t} - \tau^n_t e^n_t, \tag{34}$$

where

$$\dot{k}^n_{j,t} = i^n_{j,t} - \delta k^n_{j,t}, \tag{35}$$

$$e^n_{j,t} = A^n_t {k^n_{j,t}}^{\alpha_n} {l^n_{j,t}}^{1-\alpha_n}. \tag{36}$$

Subject to the demand constraint, the cost-minimization problem yields the real marginal cost, which can be expressed following the first-order conditions with respect to the energy firm's optimal choice of energy prices, capital, abatement investments, and the environmental policy cost, as well as the energy firm's optimal choice of labour, respectively:

$$p^e_t = \varrho^e_t + f(\mu^n_t) + \varphi^n_t \tau^n_t (1 - \mu^n_t), \tag{37}$$

$$r^e_t = \varrho^e_t \alpha_n \frac{e^n_t}{k^n_t} - \delta, \tag{38}$$

$$\tau^n_t = \frac{f(\mu^n_{j,t})'}{\varphi^n_t}, \tag{39}$$

$$w^n_t = \varrho^e_t (1 - \alpha_n) \frac{e^n_t}{l^n_t}, \tag{40}$$

where $\varrho^e_{j,t} = \varrho^e_t$ is the marginal cost component related to the same capital demand of all energy firms.

Equation (39) is the optimal condition for abatement in the energy sector: abating CO_2 emissions is optimal when marginal gain equals marginal cost. In addition, abatement effort μ^n_t is common to all energy firms as highlighted in the previous section.

3.4 Households

The household problem is approached using a CRRA utility function,[20] whereby households that are heterogeneous in their wealth a and income y, choose consumption expenditures c_t.

$$\max_{\{c_t\}} E_0 \int_0^\infty e^{-\rho t} u(c_t) dt, \tag{41}$$

where $\rho \in [0,1]$ is the time discount factor.

The household budget constraint reads:

$$\dot{a}_t = r_t^a a_t + w_t^y z_t^y + w_t^n z_t^n + \frac{z_t^y}{\bar{z}} \Pi_t^F + T_t - c_t, \tag{42}$$

where a_t is the households' choice of asset with r_t^a the interest rate. z_t^y is the vector of labour productivity for households working for non-energy firms, while z_t^n is the corresponding vector of labour productivity for household working for energy firms. For simplicity, income is assumed to have two states $z_t^s \in \{z_1, z_2\}$ for each sector $s \in (y, n)$ and to follow similar Poisson processes with intensities $\lambda(jj')$,[21], while w_t^y and w_t^n are wages for both non-energy and energy labour (l_t^y and l_t^n), which is supplied inelastically by households. Finally, profits from monopolistic intermediate firms are transferred to households proportional to their income productivity levels z_t^y as in Ahn et al. [2018], where $\bar{z}$ is the average productivity.[22]

Individuals also face a borrowing constraint:

$$a_t \geq \underline{a}, \tag{43}$$

where $-\infty < \underline{a} < 0$.

Given this model setup, individual consumption–saving decisions and the evolution of the joint distribution of their income and wealth can be summarized with two differential

[20] $u(c) = \frac{c^{1-\sigma}}{1-\sigma}$.

[21] In our setup $j = 1, 2$. As in Ahn et al. [2018] we adopt the convention that $j = 1$ and $j' = 2$.

[22] This is meant to minimize the redistribution implied by cyclical fluctuations in profits.

equations: a HJB equation and a Kolmogorov Forward (or Fokker–Planck) equation:

$$\rho v(a,z_j^y,z_j^n,t) = \max_c u(c) + \partial_a v(a,z_j^y,z_j^n,t)(r(t)^a a + w(t)^n z_j^n + w(t)^y z_j^y + \frac{z_j^y}{\bar{z}}\Pi_t^F + T - c)$$
$$+ \sum_{j'} \lambda_{jj'} v(a,z_{j'}^y,z_{j'}^n,t) + \partial_t v(a,z_j^y,z_j^n,t), \tag{44}$$

and

$$\partial_t g(a,z_j^y,z_j^n,t) = -\partial_a[s(a,z_j^y,z_j^n,t)g(a,z_j^y,z_j^n,t)] + \sum_{j'} \lambda_{j'j} g(a,z_j^y,z_j^n,t). \tag{45}$$

with the first order condition yielding the optimal consumption sequence $c(a,,z_j^y,z_j^n,t) = u'^{-1}(\partial_a v(a,z_j^y,z_j^n,t))$.

3.5 Public Authorities

The public authority could set a carbon price (equation (46)) to meet the net-zero objectives as follows:

$$\tau_t^s = \text{Carbon Price}_t^s, \tag{46}$$

where Carbon Price$_t^s$ is the price level for the energy and non-energy sectors $s \in \{y,n\}$ that the public authority sets.

Or alternatively/equivalently,[23] the public authority could chose to follow an emission cap system, where it sets an emission cap as follows:

$$E_t^s = \text{Carbon Cap}_t^s, \tag{47}$$

with Carbon Cap$_{t=0}^s$ the actual emission level and Carbon Cap$_{t=2050}^s$ the net-zero objective (i.e. Carbon Cap$_{t=2050}^s = 0$). This cap then implies a price for carbon, depending on the level of production, the abatement cost, and carbon intensity.

The government uses the environmental policy revenues $\tau_t^s E_t^s$ to finance exogenous expenditures G_t and transfers to households T_t. The public authority budget constraint reads as:

$$G_t + T_t = \sum_s \tau_t^s E_t^s, \tag{48}$$

[23]Under an equivalent calibration.

with $\sum_s \tau_t^s E_t^s = \int_0^1 (\tau_t^e e_{j,t}^y + \tau_t^n e_{j,t}^e) dj$.

3.6 No Arbitrage

Households hold all assets in the economy and thus are subject to a unique asset return r_t^a. Both the no-arbitrage condition and the share of capital between sectors yield the capital level invested in each sector (i.e. the energy and non-energy sectors):

$$r_t^a = r_t^y = r_t^e, \tag{49}$$

and

$$K_t = K_t^y + K_t^n, \tag{50}$$

where K_t^y and K_t^n are the aggregate capital stock in each sector.

3.7 Equilibrium and Market Clearing

An equilibrium in this framework is defined as pathways for individual household and firm decisions $\{a_t, c_t, l_t^y, l_t^n, e_t^n, k_t\}_{t\geq 0}$, input prices $\{w_t^y, w_t^n, p_t^e\}_{t\geq 0}$, returns on assets $\{r_t^a\}_{t\geq 0}$, fiscal variables $\{T_t, G_t, \tau_t\}_{t\geq 0}$, measures $\{\nu_t\}_{t\geq 0}$, and aggregate quantities such that, at every time t: (i) households and both types of firms maximize their objective functions taking as given equilibrium prices, taxes, and transfers; (ii) the sequence of distributions satisfies aggregate consistency conditions; (iii) the government budget constraint holds; and (iv) all markets clear. There are three markets in our economy: the market for capital of energy and non-energy firms (that can be glossed as a single asset), the labor market, and the goods market.

The asset market clears when physical capital K_t equals households' holdings of assets $A_t = \int a d\nu_t$,

$$K_t = A_t. \tag{51}$$

The labor market clears as follows:

$$L_t^s = \int z^s l_t^s(a, z^y, z^n) d\nu_t, \tag{52}$$

where s represents our two sector (i.e. energy and non-energy).

The goods market clearing condition reads as:

$$Y_t = C_t + I_t + G_t + \sum_s F(\mu_t^s), \tag{53}$$

where Y_t is the aggregate output, C_t is total consumption expenditure, $I_t = I_t^y + I_t^n$ aggregate investment in total capital K_t. $F(.) = \int_0^1 f(.)dj$ is the aggregate abatement cost for each sector s.

4 Solution Method

In this section, we describe the general solution framework necessary to solve our model. We then detail the custom MATLAB algorithm we developed to address specific issues related to having climate dynamics in the model.

4.1 Method

To solve our heterogeneous-agent model, the first step is to find a stationary equilibrium. The consumer's problem is solved on a grid using finite differences à la Achdou et al. [2022]. We discretize time in addition to wealth and income. The income process follows a two state Poisson and we construct a linearly-spaced asset grid with 201 points. The dynamic programming problem is then solved by evaluating the value function using an upwind scheme finite difference method.[24]

Stationary equilibrium:

A stationary recursive competitive equilibrium is defined as:

1. Value and policy functions: $v(a, z^y, z^n)$, $c(a, z^y, z^n)$, and $s(a, z^y, z^n)$
2. Factor demands: K and L^s
3. Distribution of household wealth: $g(a, z^y, z^n)$

[24] For further details about the method, please refer to Achdou et al. [2022].

4. Prices: r^a, p^e, w^y, and w^n

such that:

1. Given a set of prices r^a, w^y, and w^n, the value function $v(a, z^y, z^n)$ solves the household problem, thus satisfying the HJB equation:

$$\rho v(a, z_j^y, z_j^n) =$$
$$\max_c u(c) + \partial_a v(a, z_j^y, z_j^n)(r(t)^a a + w^n z_j^n + w^y z_j^y + \tfrac{z_j^y}{\bar{z}}\Pi^F + T - c) + \textstyle\sum_{j'} \lambda_{jj'} v(a, z_{j'}^n, z_{j'}^y)$$

   on $(\underline{a}, \infty)$ and for $j \in (1{,}2)$, which implies policy and saving functions: $c(a, z^y, z^n) = (u')^{-1}(\partial_a v(a, z^y, z^n))$ and $s(a, z^y, z^n) = (1 + r^a)a + w^y z^y + w^n z^n + T + \frac{z_j^y}{\bar{z}}\Pi^F - c(a, z^y, z^n)$

2. Given the prices r^a, p^e, w^y, and w^n, the factor demands K and L^s, solve the intermediate and energy firms first order conditions,

3. Given the saving policy function $s(a, z^y, z^n)$, the distribution $g(a, z^y, z^n)$ satisfies the stationary Kolmogorov Forward equation:

$$0 = -\partial_a[s(a, z_j^y, z_j^n)g(a, z_j^y, z_j^n)] + \textstyle\sum_{j'} \lambda_{j'j} g(a, z_j^y, z_j^n)$$

   on $(\underline{a}, \infty)$ and for $j \in (1{,}2)$,

4. Given the distribution $g(a, z, z^n)$, the markets for capital and labor clear:

$$\textstyle\sum_j \int_{\underline{a}}^{\infty} a g(a, z_j^y, z_j^n) da = K \text{ and } \sum_j z_j^s f_j^s = L^s.$$

Transition dynamics:

Turning now to the transition dynamics, we define the time-dependent recursive competitive equilibrium as:

1. Value and policy functions: $v(a, z^y, z^n, t)$, $c(a, z^y, z^n, t)$, and $s(a, z^y, z^n, t)$

2. Factor demands: $K(t)$ and $L(t)^s$
3. Distribution of household wealth: $g(a, z^y, z^n, t)$
4. Prices: $r^a(t)$, $p(t)^e$, $w(t)^y$, and $w(t)^n$

such that:

1. Given a set of prices $r(t)^a$, $w(t)^y$, and $w(t)^n$, as well as a terminal condition for the value function $v_\infty(a, z_j^y, z_j^n)$, the value function $v(a, z^y, z^n, t)$ solves the dynamic household problem, and satisfies the HJB equation:

$$\rho v(a, z_j^y, z_j^n, t) = \max_c u(c) + \partial_a v(a, z_j^y, z_j^n, t)(r(t)^a a + w(t)^n z_j^n + w(t)^y z_j^y + \tfrac{z_j^y}{\bar{z}}\Pi_t^F + T_t - c)$$
$$+ \textstyle\sum_{j'} \lambda_{jj'} v(a, z_{j'}^y, z_{j'}^n, t) + \partial_t v(a, z_j^y, z_j^n, t)$$

with the terminal condition $lim_{T\to\infty} v(a, z_j^y, z_j^n, T) = v_\infty(a, z_j^y, z_j^n)$

2. Given the prices $r(t)^a$, $p(t)^e$, $w(t)^y$, and $w(t)^n$, the factor demands $K(t)$ and $L(t)^s$ solve the intermediate and energy firms first order conditions,

3. Given the saving policy function $s(a, z^y, z^n, t)$ and the initial distribution $g_0(a, z_j^y, z_j^n)$, the distribution $g(a, z^y, z^n, t)$ satisfies the dynamic Kolmogorov Forward equation:

$$\partial_t g(a, z_j^y, z_j^n, t) = -\partial_a[s(a, z_j^y, z_j^n, t) g(a, z_j^y, z_j^n, t)] + \textstyle\sum_{j'} \lambda_{j'j} g(a, z_j^y, z_j^n, t)$$

with an initial condition on the distribution $g(a, z_j^y, z_j^n, t) = g_0(a, z_j^y, z_j^n)$,

4. Given the distribution $g(a, z^y, z^n, t)$, the markets for capital and labor clear:

$$\textstyle\sum_j \int_{\underline{a}}^\infty a g(a, z_j^y, z_j^n, t) da = K(t) \text{ and } \sum_j z_j^s f_j^s = L(t)^s.$$

4.2 Solution Algorithm under Climate Dynamics

Contrary to standard models with idiosyncratic income risk, climate dynamics in our model imply different methods for finding the initial and final steady states. With the initial and final steady states in hand, we proceed to compute transition pathways following

MIT shocks. In what follows, we rely on Achdou et al. [2022] for solving the HJB and Kolmogorov Forward equations and adapt their method to our Aiyagari [1994] framework with two production sectors and an environmental externality.

Initial state

For the initial steady state, the procedure is fairly standard, as emissions and temperature are fixed at the current level. Compared to the Aiyagari [1994] framework, however, our model features two types of capital. While looping over values for aggregate capital, we exploit the no-arbitrage condition and build an inner loop where we guess a share of aggregate capital going to the energy sector. We then use firms' first order conditions to ensure that returns on capital in both sectors are equal (i.e. the share of capital guessed clear the no-arbitrage condition), before aggregating household wealth and checking that our market clearing conditions hold.

Final state

For the final state, the presence of climate dynamics complicates the search for a fixed point (i.e. the final steady state level of temperature and stock). To understand why, consider equation (13) evaluated at the steady state:[25]

$$\bar{T}^o = \phi_2 \bar{X}. \tag{54}$$

While the parameter ϕ_1 does not appear in the steady state equation, it plays an important role in temperature dynamics over the transition. It is also not possible to know the terminal value of X without knowing the path of emissions over the period studied. To address these issues, we compute a synthetic path for emissions consistent with the Representative Concentration Pathway (RCP) 8.5 scenario,[26] which allows us to get the terminal value of

[25] $\bar{T}^o$ and $\bar{X}$ represent the steady state values.

[26] In RCP 8.5 emissions continue to rise throughout the 21st century.

X and T. With the value of temperature at the final state, we are then able to compute the remaining terminal values within the inner loop used to find the level of capital in each sector.

Transition dynamics

For transition dynamics, we rely on the same method developed for finding the final state of the economy. The only difference is that we now need to find the full path of all the endogenous variables. To do so, we use a vector of synthetic emissions fitted to the studied scenario to retrieve the complete path of temperature. We then derive the vector of output subject to climate damages. The remaining part of the procedure is standard.

4.3 Calibration

The model is calibrated on U.S. data. While we do not have two assets (liquid and illiquid as in Kaplan et al. [2018]), which would otherwise allow for a refined representation of U.S. households portfolios, we calibrate income shocks to retrieve a realistic distribution of wealth.[27] The wide range of assets found in the economy is represented in our model as a generic productive asset that households hold and are allowed to borrow. We set the borrowing constraint $\underline{a}$ to a value corresponding to roughly one year of average wages. For simplicity, the income process within each sector follows a two-state Poisson, representing high and low income realizations. The productivity of high earners compared to low earners is proportional across sectors.

For parameters related to standard macroeconomic theory, their calibration is in line with the literature: the share of hours worked is set at one third in each sector and the coefficient of relative risk aversion σ in the CRRA utility function is set at 2. Discount rate ρ is set at 5 percent to target an interest rate of about 4 percent annually. The depreciation rate of capital δ is calibrated at 5 percent annually. Turning to the production sector, the elasticity of substitution θ is set at 6, leading to a markup of around 17 percent. The non-energy sector

[27] The scope of our paper being the transition to net-zero, we are more interested in the dynamics of the distribution rather than the initial steady state.

relies on three inputs. We set α_1 and α_2 to target an energy production to total output ratio of 4-5 percent. The share of labour in production for non-energy firms is set at 0.66, while the share of capital α_1 is set at 0.19, and the share of energy α_2 at 0.15. We use sectoral data on the U.S. to set the share of the energy sector α_n at two thirds, which allows us to recover the share of wages from the energy sector with respect to the non-energy sector, and to account for large investment needed in this sector. These calibrations lead to an average labor share of 57 percent and an average capital and profit share of 26 percent.

Regarding environmental components, we calibrate the damage function according to Dietz and Stern [2015]. The global temperature parameters ϕ_1^o and ϕ_2^o are set following Dietz and Venmans [2019] to pin down the 'initial pulse-adjustment timescale' of the climate system.[28] Abatement parameters θ_1 and θ_2, which represent the abatement costs for each sector, are borrowed from Nordhaus [2008].[29] To match the U.S. level share of emissions from each sector (25 percent of total emissions generated by the energy sector), we calibrate the emission-to-sectoral-production ratio $\bar{\varphi}^y$ and $\bar{\varphi}^n$ to 2 and 0.3 respectively. Finally, the decoupling rate of emissions is calibrated to 1 percent to match U.S. Energy Information Administration (EIA) data.

TABLE I

Model Matching Moments

Target	Model	Data	Source
Macro Aggregates:			
Labor Share	0.567	0.597	FRED (2019)
Capital Share	0.260	0.311	BEA (2020)
Environmental Aggregates:			
Global Level of Carbon Stock (GtC)	840	840	USDA (2020)
Temperature °C (in excess to pre-industrial level)	1.15	1.19	NOAA (2020)
Share of Emissions from Energy	0.25	0.25	EIA (2020)
Share of Emissions from Non-Energy	0.75	0.75	EIA (2020)
Emissions Decoupling Rate	0.01	0.01	EIA

[28] We perform a sensitivity analysis on the damage function using values from Nordhaus and Moffat [2017] and Weitzman [2012], in the next section. We also perform a robustness analysis on climate sensitivity using various values of ϕ_2^o.

[29] We assume that firms from both sectors have access to the same abatement technology. We also perform sensitivity analysis on the efficiency of abatement technology in the next section.

5 Net-Zero Transition Results

5.1 Understanding the Impact of Carbon Pricing under Heterogeneous Agents

In this section we will investigate the impact of putting a price on carbon in an economy with idiosyncratic income risk. Using our model, we compute the transition following an MIT shock under three different scenarios that all trigger a 25-percent reduction in total emissions.[30] Our main scenario relies on carbon taxation on both the energy and the non-energy firms. We also assess how solely taxing either energy firms or non-energy firms would change the outcome of the policy. We then disentangle theoretically and compute numerically how pricing carbon on the firm side ultimately affects household consumption according to level of income and wealth.

5.1.1 Energy Sector, Carbon Pricing, and Macroeconomic Drivers

We first focus on how carbon price shocks, when set at the energy sector level, propagate through the economy and impact macroeconomic prices and aggregates. When the regulator sets a carbon price, energy firms are forced to engage in abatement efforts and to pay a carbon price. In doing so, the demand for energy decreases, which increases energy prices and decreases wages and returns. This result holds as long as the drop in energy generation is higher than the total environmental cost. Otherwise, energy prices fall on impact:

$$\underbrace{p_t^e}_{\text{Energy Price}} = (\underbrace{mc_t}_{\text{Total Marginal Cost}} - \underbrace{\underbrace{f(\mu_t^y)}_{\text{Abatement Investment}} - \underbrace{\tau_t^y(e_t^y/y_t)}_{\text{Emission Intensity Carbon Price}}}_{\text{Total Environmental Costs}})\alpha_2 \frac{y_t}{e_t^n} \tag{55}$$

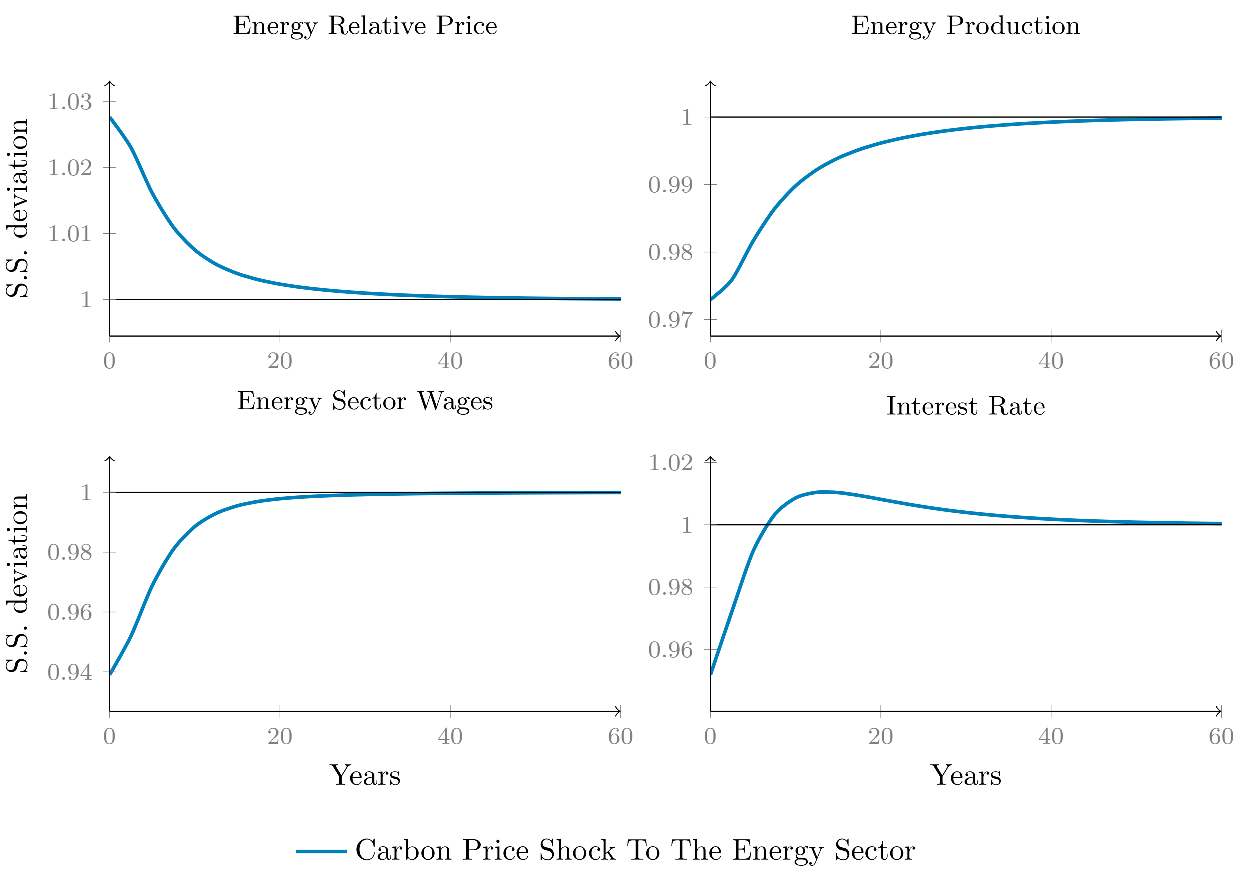
$$r_t^e = (\underbrace{p_t^e}_{\text{Energy Price}} - \underbrace{\underbrace{f(\mu_t^n)}_{\text{Abatement Investment}} - \underbrace{\tau_t^n(e_t^e/e_t^n)}_{\text{Emission Intensity Carbon Price}}}_{\text{Total Environmental Costs}})\alpha_n \frac{e_t^n}{k_t^n} - \delta \tag{56}$$

[30]We conduct this exercise by setting the carbon price $\tau_t^s = \varepsilon_t^s$ following a bounded Ornstein-Uhlenbeck process: $d\varepsilon_t^s = \theta^s(\hat{\varepsilon}^s - \varepsilon_t^s)dt + \sigma^s dB_t$. B_t is a F_t-adapted idiosyncratic Brownian motion and θ^s, $\hat{\varepsilon}^s$, and σ^s are positive constants. $s \in \{n, y\}$ represents the energy and non-energy sectors.

$$w_t^n = (\underbrace{p_t^e}_{\text{Energy Price}} - \underbrace{\underbrace{f(\mu_t^n)}_{\text{Abatement Investment}} - \underbrace{\tau_t^n(e_t^e/e_t^n)}_{\text{Emission Intensity Carbon Price}}}_{\text{Total Environmental Costs}})(1-\alpha_n)\frac{e_t^n}{l_t^n} \tag{57}$$

As shown in figure VI, following a carbon price shock that aims at reducing emissions by 25 percent, energy prices increase, whereas energy generation, as well as wages and returns, decrease. These results are consistent with our empirical findings for the case of California outlined in the previous empirical section. Energy firms decide to reallocate resources by lowering their capital investment level and decreasing labor wages. Firms then increase energy prices to recover profit loss. This increase in energy prices decreases the intermediate firms' demand for energy and thus decreases the total energy generation level.

FIGURE VI. Energy Sector Carbon Pricing and Macroeconomic Aggregates



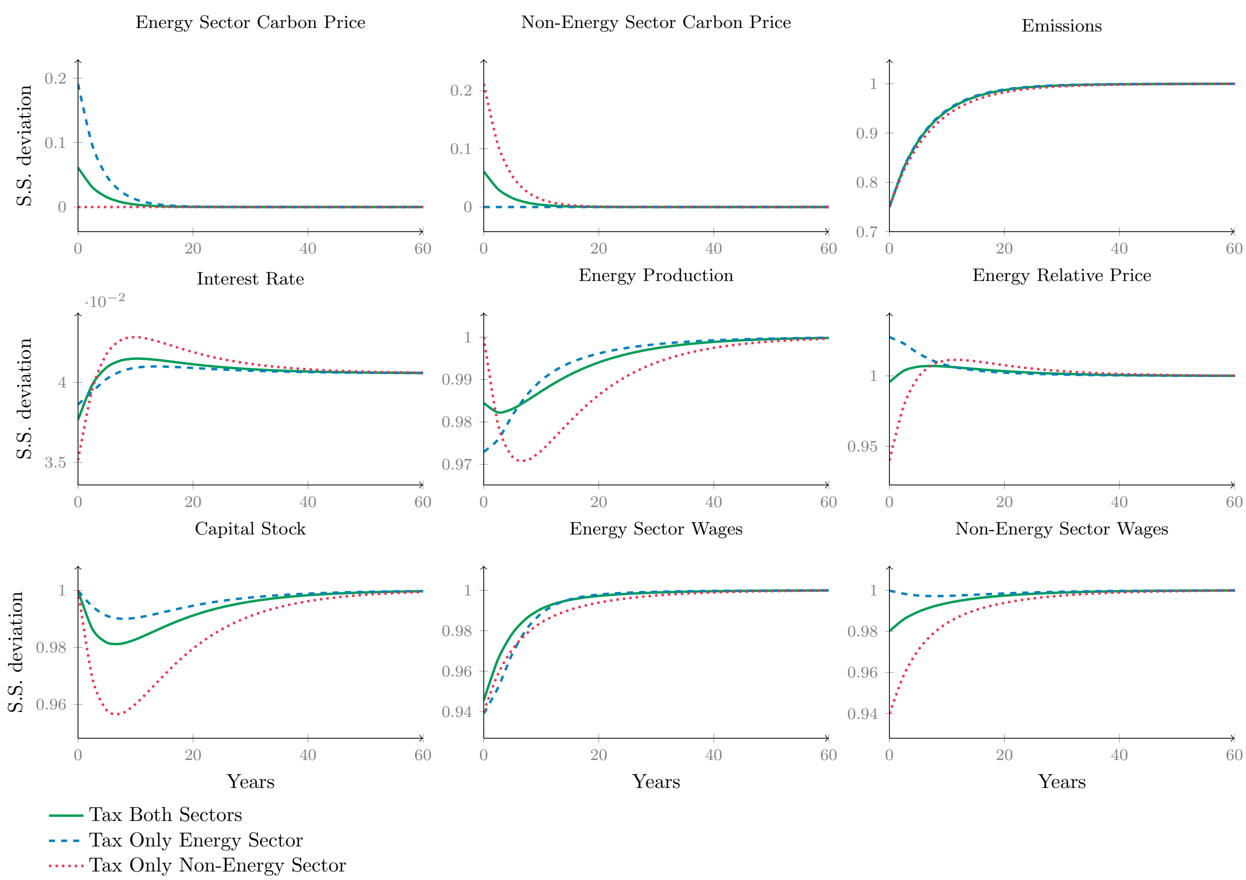
Note: The figure plots the impulse responses to a carbon shock leading to an initial 25% reduction in total emissions in the energy sector as deviation from a normalized steady state.

In the next exercise, we explore three scenarios where the public authority sets carbon pricing within: i) the energy sector only, ii) the non-energy sector only, and iii) both the energy and non-energy sectors at the same time. These scenarios allow us to understand the implications of different policy design.

5.1.2 Carbon Price and Macroeconomic Dynamics

Figure VII displays the reaction of the economy to an introduction of a carbon price that engenders a 25 percent emissions reduction, under our three scenarios. In the case where the price on carbon is only applied to the non-energy sector (dotted red line), this implies cutting emissions in this sector by approximately one third. Whereas, when the price on carbon is only applied to the energy sector (dashed blue line), this represents a reduction of almost all emissions in the energy sector. Since both sectors rely on the same abatement technology, the difference in response is due to the specific role each sector plays in the economy. The energy sector being a small part of the economy, taxing it does not greatly impact the dynamics of the interest rate nor the capital stock, compared to other scenarios. However, as energy producers provide an input for the non-energy sector, implementing a carbon pricing scheme targeted to energy firms still leads to a gradual decline in the capital stock and output, since firms have to bear a higher input cost for energy.

FIGURE VII. Carbon Pricing and Macroeconomic Aggregates



Note: The figure plots three different scenarios leading to an initial 25% reduction in total emissions. The dotted red line corresponds to the case where only the non-energy sector is taxed. The dashed blue line corresponds to the case where only the energy sector is taxed. The solid green line corresponds to the case where the tax is implemented in both sectors.

When taxing energy firms as opposed to taxing non-energy firms (and vise versa), the impacts on energy prices are found to be widely different. Our simulations show that when taxing energy firms, on one hand, the increasing cost related to carbon triggers an immediate drop in energy production, implying in turn an increase in the relative price of energy. On the other hand, taxing only non-energy firms reduces the demand for energy and its relative price. Energy producers thus gradually lower their production and the price returns to its initial steady state. The situation on the market for labor also depends on the type of policy implemented. Although both non-energy and energy sector wages fall regardless of the policy implemented, the effect is comparable across scenarios in the energy sector but different in the non-energy sector. Concretely, this means that taxing non-energy firms' carbon emissions transmits to both sectors wages, when a policy implemented only in the energy sector minimally affects wages in the non-energy sector. Overall, the analysis of aggregate variables suggests that implementing a carbon fiscal policy on energy firms before targeting other firms (as is the case in Californian and European cap-and-trade schemes) is efficient, since it is less costly to first abate emissions from energy production.

5.1.3 Carbon Price Transmission Mechanism

When a regulator plans to implement carbon pricing, it is important to understand beforehand how it is going to impact household consumption according to income and wealth level. To uncover the heterogeneous effects of taxing firms' emissions on household consumption, we start by detailing direct and indirect drivers of consumption. This allow us to later tie these drivers of consumption to the empirical findings in section 2.

We first decompose the response at time zero of consumption with respect to its main components:

$$C_t(\{\Gamma_t\}_{t\geq 0}) = \int c_t(a, z^y, z^n; \{\Gamma_t\}_{t\geq 0}) d\nu_t \tag{58}$$

Here $c_t(a, z^y, z^n; \{\Gamma_t\}_{t\geq 0})$ is the household consumption policy function and $\nu_t(da, dz; \{\Gamma_t\}_{t\geq 0})$ is the joint distribution of illiquid assets and idiosyncratic income.

Following Kaplan et al. [2018],[31] by total differentiation, we can decompose the consumption response at t = 0 as:

$$dC0 = \int_0^\infty \left(\frac{\partial C0}{\partial r_t^a} dr_t^a + \frac{\partial C0}{\partial w_t^n} dw_t^n + \frac{\partial C0}{\partial w_t^y} dw_t^y + \frac{\partial C0}{\partial \Pi_t^F} d\Pi_t^F + \frac{\partial C0}{\partial T_t} dT_t \right) dt \tag{59}$$

In our framework, and opposite to Kaplan et al. [2018], we only have indirect effects of carbon price shocks to consumption, as the carbon pricing scheme studied in this paper only affects firms directly. The implementation of a carbon price will impact consumers through five channels: asset returns, both types of wages, profits, and transfers. Note that we do not consider redistributing proceeds from the carbon tax until section section 5.3, which

[31] A similar exercise can be found in Auclert [2019].

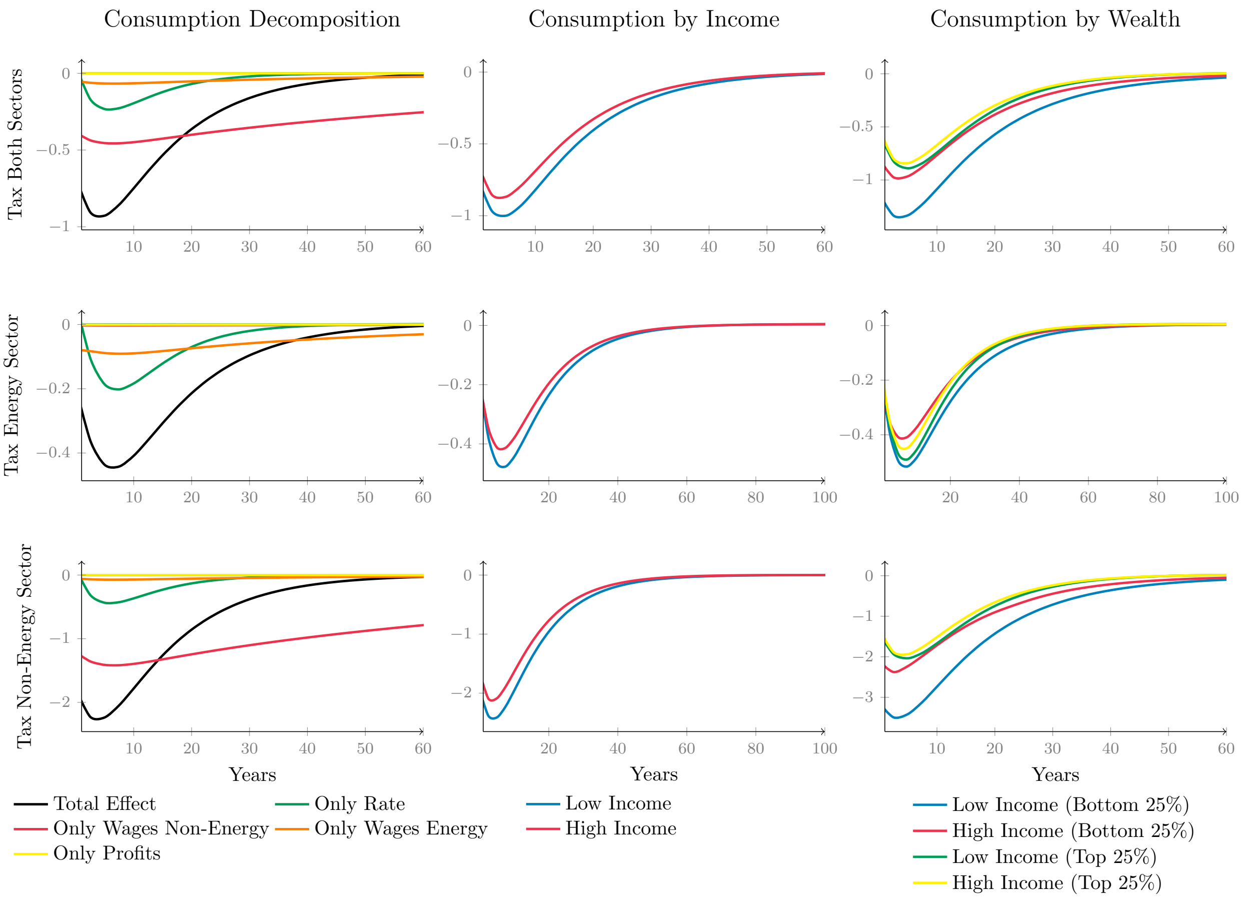
means that at present transfers will not impact consumption. Intuitively, and consistent with our empirical findings in section 2, a positive shock to the price of carbon should lead to lower asset returns, wages, and profits, as putting a higher price on carbon implies an additional input cost for firms. These effects should transmit to households and ultimately reduce consumption.

5.1.4 Distributional Effects of Carbon Pricing

Figure VIII shows the impact on consumption decomposed into various indirect effects, by income, and by wealth for our three carbon pricing scenarios. To decompose the effect, we mute all but the component of interest by setting them to their respective steady state values over the transition. Consistent with our findings on aggregate variables, the first column shows that taxing the energy sector only is the less costly policy in terms of aggregated consumption. The reason is that most of the effect goes through wages in the sector concerned by the price on carbon. Since wages from the energy sector only account for a small part of total wages, their reduction is less detrimental to consumption than a reduction of non-energy wages. As expected, changes in the interest rates put pressure on household revenues from capital, which also induces lower consumption. In the same spirit, Malafry and Brinca [2022] use a two-period heterogeneous agent model to disentangle the effect of setting a carbon price on household aggregate welfare.[32] In their setup, however, implementing a tax on carbon always benefits consumption, even without redistributing carbon revenues.

[32] The three channels they use are consumption, redistribution, and risk.

FIGURE VIII. Carbon Price Shock and Consumption Responses



Note: The figure plots the reaction of consumption according to three different scenarios leading to an initial 25% reduction in emissions. The first row corresponds to the case where the tax is implemented in both sectors. The second row corresponds to the case where only the energy sector is taxed. And the last row corresponds to the case where only the non-energy sector is taxed. The first column plots the reaction of consumption as well as its four components. The second column plots the reaction of consumption according to the realization of income. And the last column plots the reaction of consumption according to the realization of income and the level of wealth.

Columns two and three display the distributional impact for our three scenarios. We find that taxing the energy sector only generates less distributional costs than other policies. Not only the aggregate impact on consumption is smaller, but the consumption reaction for low/high income and low/high wealth is quite homogeneous compared to the other two scenarios. In the case where only the non-energy sector is subject to the carbon price, the loss in consumption for low income households that are also at the lower end of the wealth distribution is twice the loss households at the upper end of the wealth distribution experience. This suggests that policy makers should pay particular attention to distributional effects throughout the transition to net-zero. It is especially true for countries that plan to move from taxing only emissions generated in the energy sector to taxing emissions generated in all sectors.

5.2 Net-Zero Transition and Wealth Dynamics

Turning now to net-zero transition dynamics, we present and analyze various scenarios. We first highlight how incorporating climate dynamics and accounting for climate damages have a significant impact on the long-term equilibrium of the model. We also investigate the role that climate sensitivity, damage uncertainty, and abatement efficiency play on laissez-faire and net-zero emissions transitions, respectively. Finally, we show that the speed at which carbon policy is implemented matters for transition dynamics.

The baseline scenario features a trend growth rate of 2 percent annually over the period 2022 to 2100. The growth process is then stopped and we let the model converge to the new steady state. Although we use an average calibration (i.e. consistent with intermediate values found in the literature) for parameters related to climate sensitivity, climate damages, and abatement efficiency, we also provide in the appendix a detailed sensitivity analysis for each of the exercises we perform.

5.2.1 Why climate dynamics matters

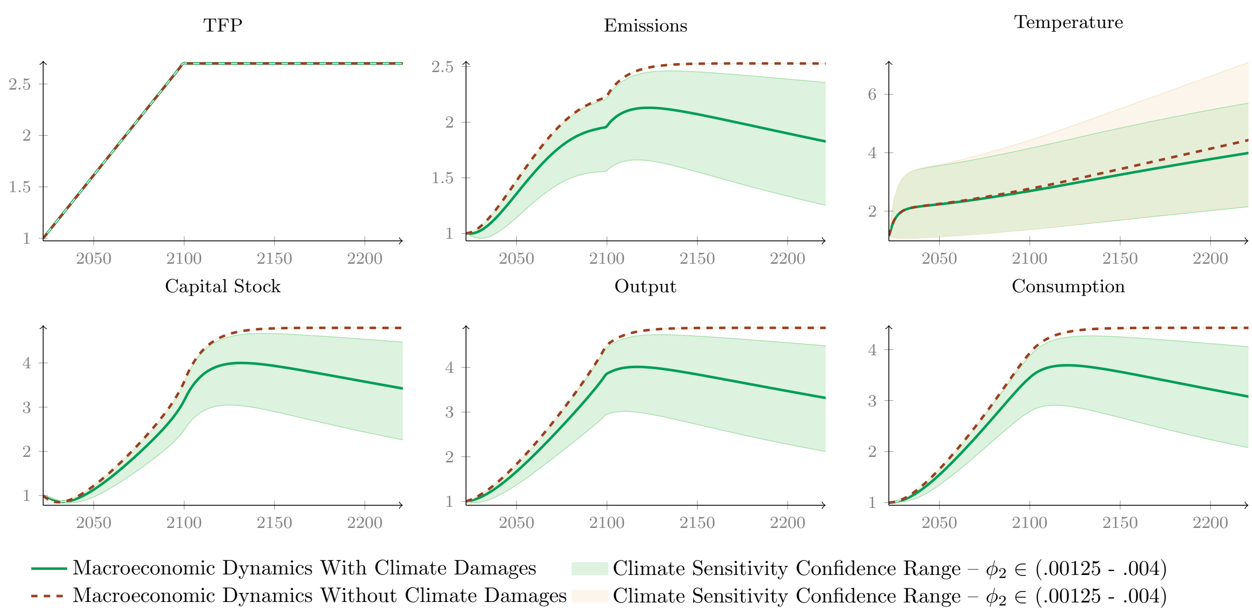
In this section, we investigate how climate feedback shapes long-term dynamics, both at the aggregate level and at the household level. We compare the simulations of our model to a counterfactual model where we remove the link between temperature and production. The objective is to assess whether ignoring climate dynamics leads to an erroneous view of what might happen to the economy and wealth distribution in the future if no action is taken.

Climate damages and laissez-faire transition pathways

Figure IX and figure X display transition pathways from our baseline model (with climate damages – green solid line) and from the counterfactual model (without climate damages

– brown dashed line). As argued by Cai and Lontzek [2019], Traeger [2021], and Van den Bremer and Van der Ploeg [2021] among others, uncertainty over climate dynamics plays a significant role in shaping macroeconomic dynamic responses. As such, we provide transition dynamics taking into account a range of values for ϕ_2, which corresponds to the uncertainty over climate dynamics in our framework.

FIGURE IX. Climate Uncertainty and Macroeconomic Dynamics – Macro Aggregates



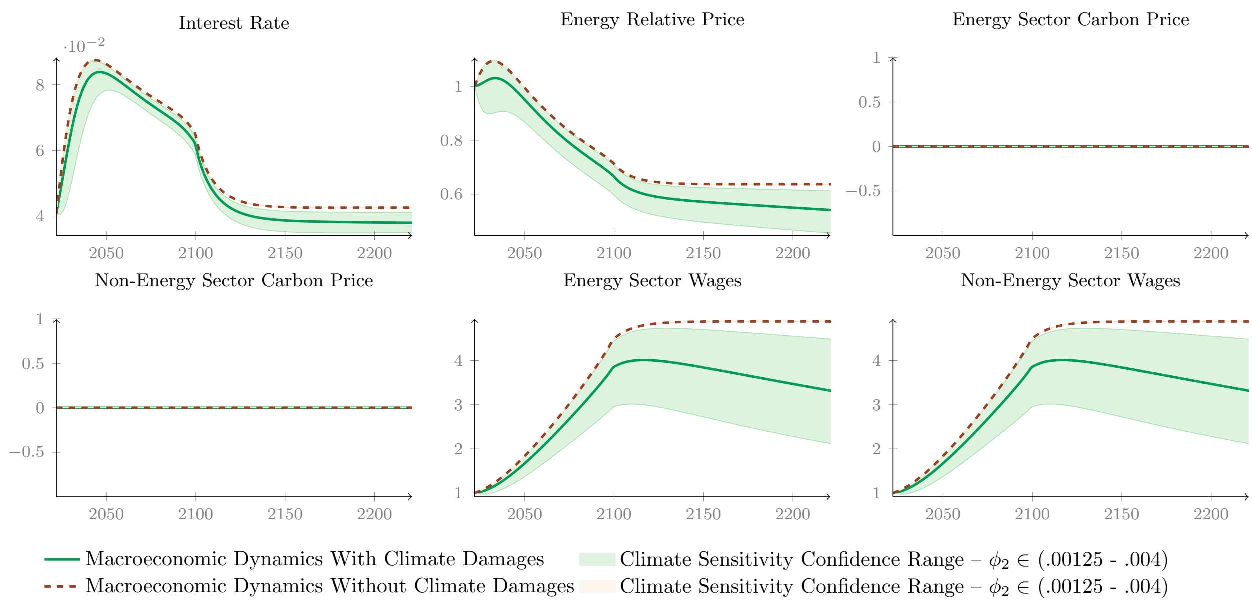
Note: The figure compares transitions computed using a model without climate damages (dashed brown line) to transitions computed using a model with climate damages (solid green line). Brown and green confidence ranges represent confidence range for values of ϕ_2 in line with IPCC scenarios.

In both scenarios, economic activity increases the flow and stock of emissions (as firms do not internalize the climate externality), yielding a temperature level $T^o_{2100} \in$ (2.8°C - 3.5°C) by 2100.[33] The simulations in figure IX show that, when taking into account the effect of climate change on productivity, output and capital start to decline rapidly once the growth process is over. Thus, failing to account for climate change leads to overestimating GDP and consumption in the long run. As output decreases compared to the case where temperature does not impact productivity, energy demand falls and wages in both sectors are reduced (figure X). Interestingly, the energy relative price is also lower in this case, since

[33] We choose the range of ϕ_2 to match the latest IPCC RCP scenarios.

demand for energy plummets. In addition, as households expect sustained long-run economic growth, they increase their consumption, substituting away from capital savings in the first few periods, which increase the return on capital firms have to pay. As the growth process stops in 2100, households anticipate and start smoothing their consumption, bringing the interest rate back to a level close to its initial steady state.

FIGURE X. Climate Uncertainty and Macroeconomic Dynamics – Prices



Note: The figure compares transitions computed using a model without climate damages (dashed brown line) to transitions computed using a model with climate damages (solid green line). Brown and green confidence ranges represent confidence range for values of ϕ_2 in line with IPCC scenarios.

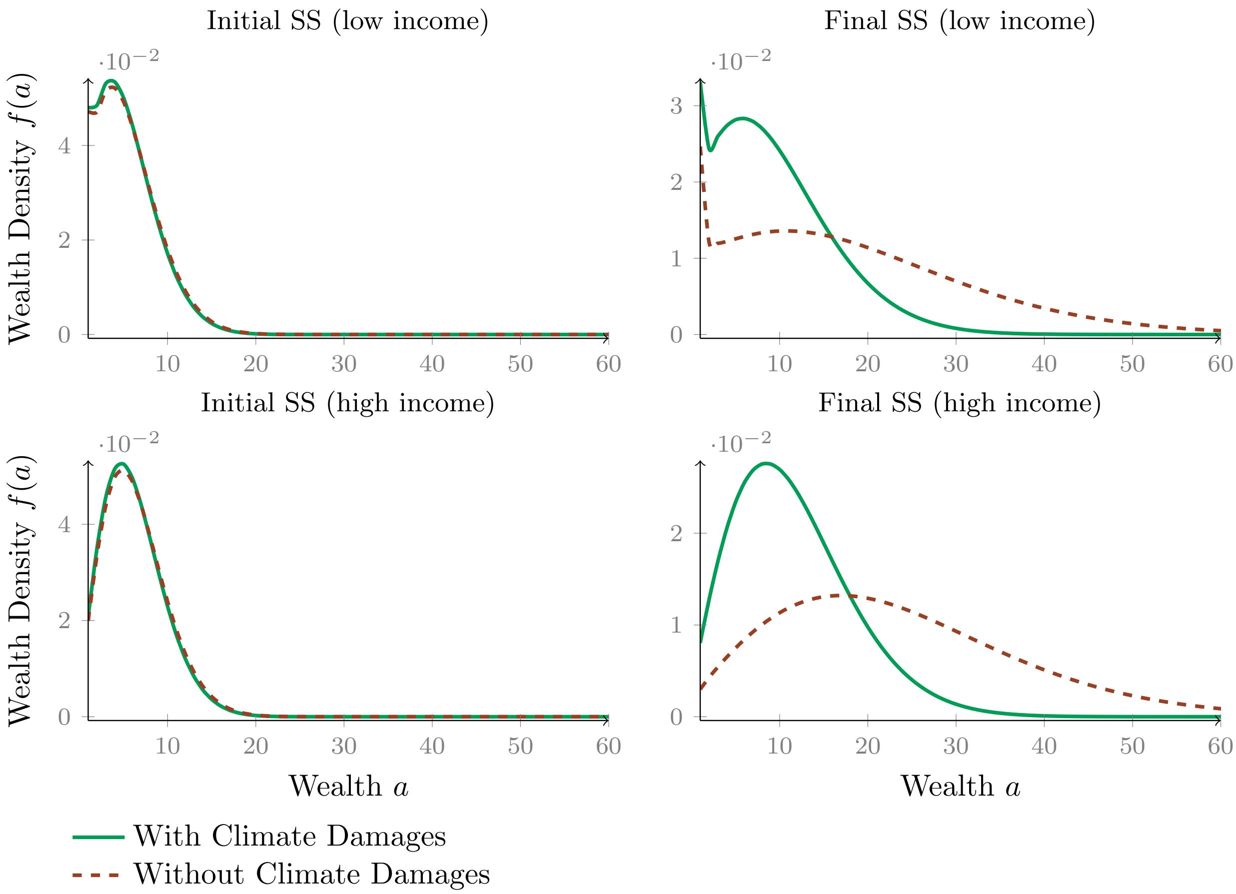
Similarly, uncertainty over climate damages (figure XXIX and figure XXX) plays an important role over the transition. While there appears to be less uncertainty about damages compared to climate sensitivity, the range of economic losses remains large enough to motivate aggressive mitigation policies.

Overall, the sensitivity analysis on climate and damages shows that accounting for climate dynamics and uncertainty is crucial to derive credible long-term scenarios. Therefore, models that do not include this type of mechanism are likely to yield biased results and lead to myopic policy recommendations. An interesting additional question concerns the consequences of ignoring climate dynamics on the study of the distribution over time.

Implications for the distribution of wealth

Figure XI displays initial and final stationary distributions from our baseline model (with climate damages) and our counterfactual model (without climate damages). One can see that what was true for aggregate variables is even more relevant for distributional costs. When ignoring the negative feedback from temperature to productivity, the distribution of wealth flattens and drastically shifts to the right, which means that the average household becomes significantly wealthier. However, correcting for the impact of climate paints a completely different picture. In this more realistic case, the decrease in distributional costs is marginal, despite 80 years of sustained economic growth. In other words, when global warming goes unchecked, it has the ability to destroy gains from increased productivity. This fact, along with the other findings in this section, motivates our choice to include climate damages and take uncertainty into account when studying the distributional impacts of carbon policy during the transition to net-zero.

FIGURE XI. Distribution Impacts With and Without Climate Damages



Note: The figure compares initial and final stationary distributions computed using a model without climate damages (dashed brown line) to transitions computed using a model with climate damages (solid green line).

5.2.2 Meeting the Net-Zero Target

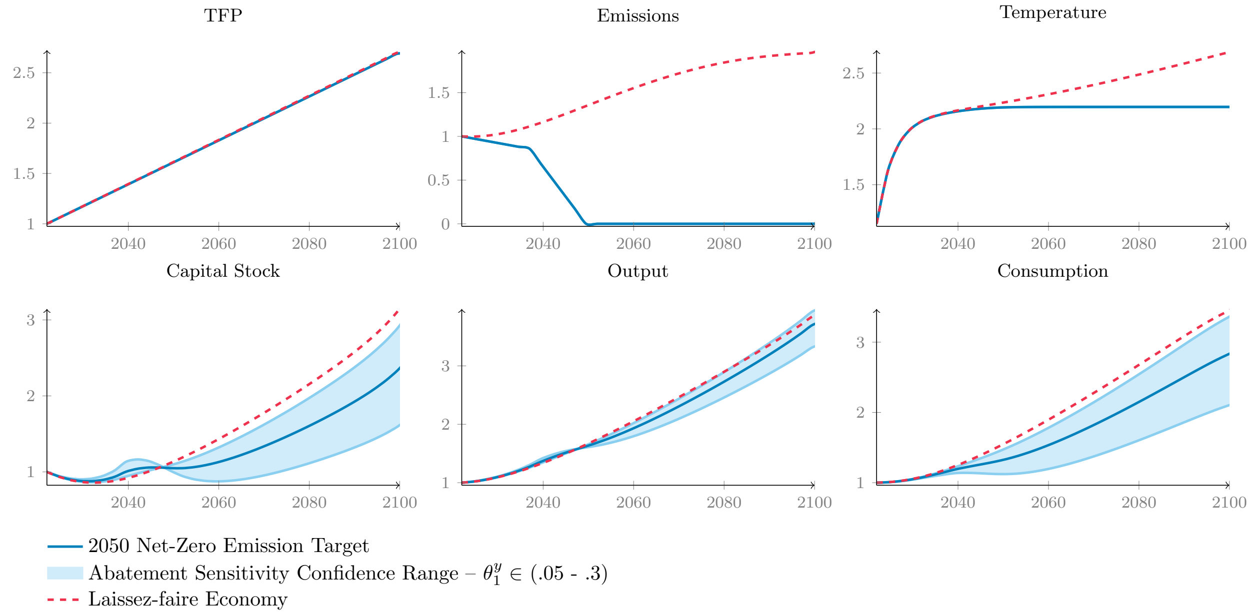
We now investigate the transition pathways over the net-zero emission target scenario. We first start by showing how abatement technologies play a pivotal role in shaping the transition pathways as well as the wealth distribution along the transition. More precisely, we analyze how different levels of abatement costs for firms lead to more or less significantly different macroeconomic responses and severe distributional impacts from a rising carbon price.

Net-zero objective transition pathways

A large part of the literature focuses on the optimal path of carbon pricing (e.g. Golosov et al. [2014], Dietz and Venmans [2019], Cai and Lontzek [2019], among many others). The main question then is whether the optimal carbon price is able to achieve net-zero emissions by 2050. When accounting for different levels of uncertainty (e.g. climate damages, climate sensitivity, and abatement technology efficiency, among others), achieving such a target is severely hindered. Benmir and Roman [2020] show how optimal policy is not sufficient and investigate, using a representative agent (RA) macro model, the implication of gradually setting the carbon cap to meet a net-zero objective by 2050. However, Benmir and Roman [2020] do not specifically model energy sectors and focus on green and brown sectors. Including energy producers allows for investigating sequential policy setting and the implications on the macroeconomy.

In figure XII we compare the laissez-faire scenario to a cap policy leading to net-zero emissions by 2050. We show how under a 2 percent growth rate, a laissez-faire scenario clearly overshoots the Paris Agreement objective of keeping temperature below 2^{o}C with temperature rising to a level above 2.5^{o}C. In contrast, a net-zero strategy where emissions are reduced linearly and gradually across sectors as is the case for most cap-and-trade regimes (in our case, the cap first targets the energy sector before spanning all non-energy sectors 15 years later), allows for maintaining a temperature below 2.2^{o}C. Furthermore, the cap policy induces a loss in the capital used to produce energy, leading to both a consumption and output loss for the net-zero case. During the transition this also means greater distributional and welfare (as it will be highlighted in the next section) costs. However, this effect does not hold in the long run. As the effects of global warming start materializing, output deteriorates in the laissez-faire case and the gains from not transitioning to net-zero are quickly reversed.

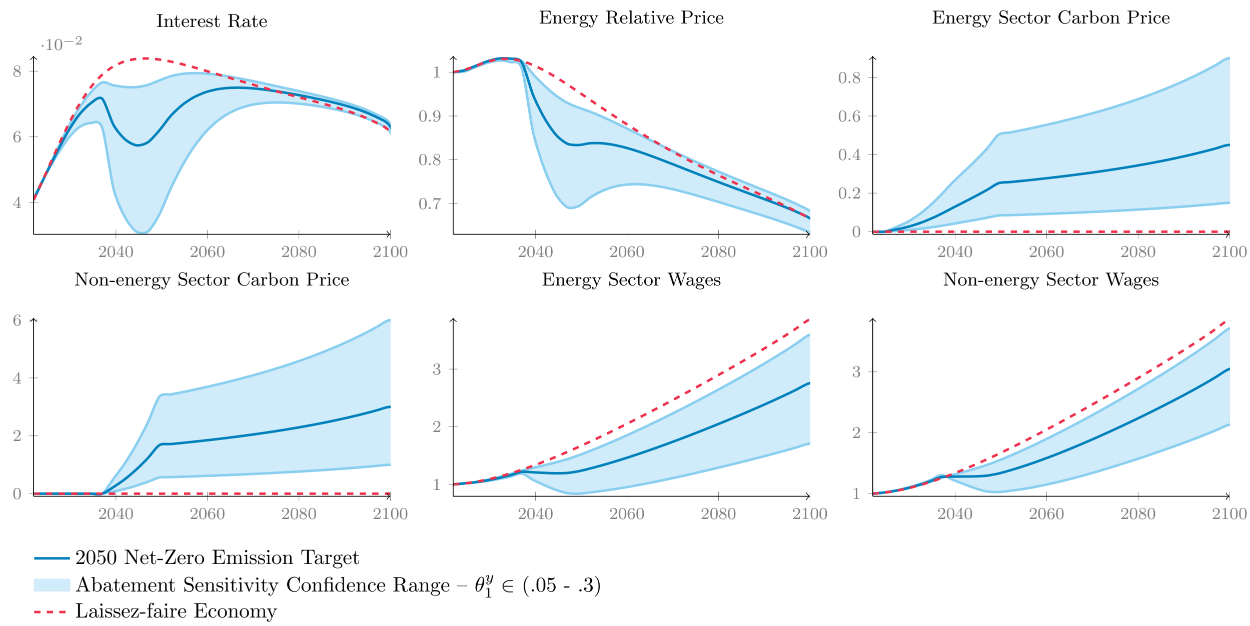
FIGURE XII. Net-Zero Emission Target and Laissez-faire Economy – Macro Aggregates



Note: This figure compares the net-zero scenario to a laissez-faire scenario under a 2 percent growth rate over the period 2022 t0 2100. We perform a sensitivity analysis (blue shaded area) over abatement efficiency (i.e. abatement cost parameter θ_1).

Turning now to prices as shown in figure XIII, our HA model under the net-zero policy induces a rise in carbon prices, energy price, and interest rate over the first cap period where only the energy sector is subject to the environmental policy. When the regulator generalizes the cap policy to all other sectors, the interest rate, the energy price, and wages in all sectors decrease to levels significantly lower then in the laissez-faire scenario. Intuitively, there are two trusts in play. First, growth expectations trigger higher levels of consumption within households as they expect higher income in the near future, which reduces investment levels (i.e. substitution effect is higher than income effect in this case). Second, future carbon policy expectations cool down the heat generated by the growth expectations, as when the cap hits all non-energy sectors, the continuously higher levels of carbon prices reduce profits and capital demanded, which in turns decreases wages and other aforementioned factor prices.

FIGURE XIII. Net-Zero Emission Target and Laissez-faire Economy – Prices



Note: This figure compares the net-zero scenario to a laissez-faire scenario under a 2 percent growth rate over the period 2022 t0 2100. We perform a sensitivity analysis (blue shaded area) over abatement efficiency (i.e. abatement cost parameter θ_1).

Welfare Costs: Laissez-faire versus Net-zero

We find that implementing a net-zero policy by 2050 is welfare enhancing compared to the case of the laissez-faire (as shown in table II) where no environmental policy is enforced by the regulator. The net-zero emission target allows for temperature to remain below 2.2^{o}C in the long-run. Keeping temperature below 2.2^{o}C reduces the damages related to increasing temperatures, which in the case of the laissez-faire have increasing impacts on productivity.

TABLE II

Welfare: Laissez-faire and Net-zero

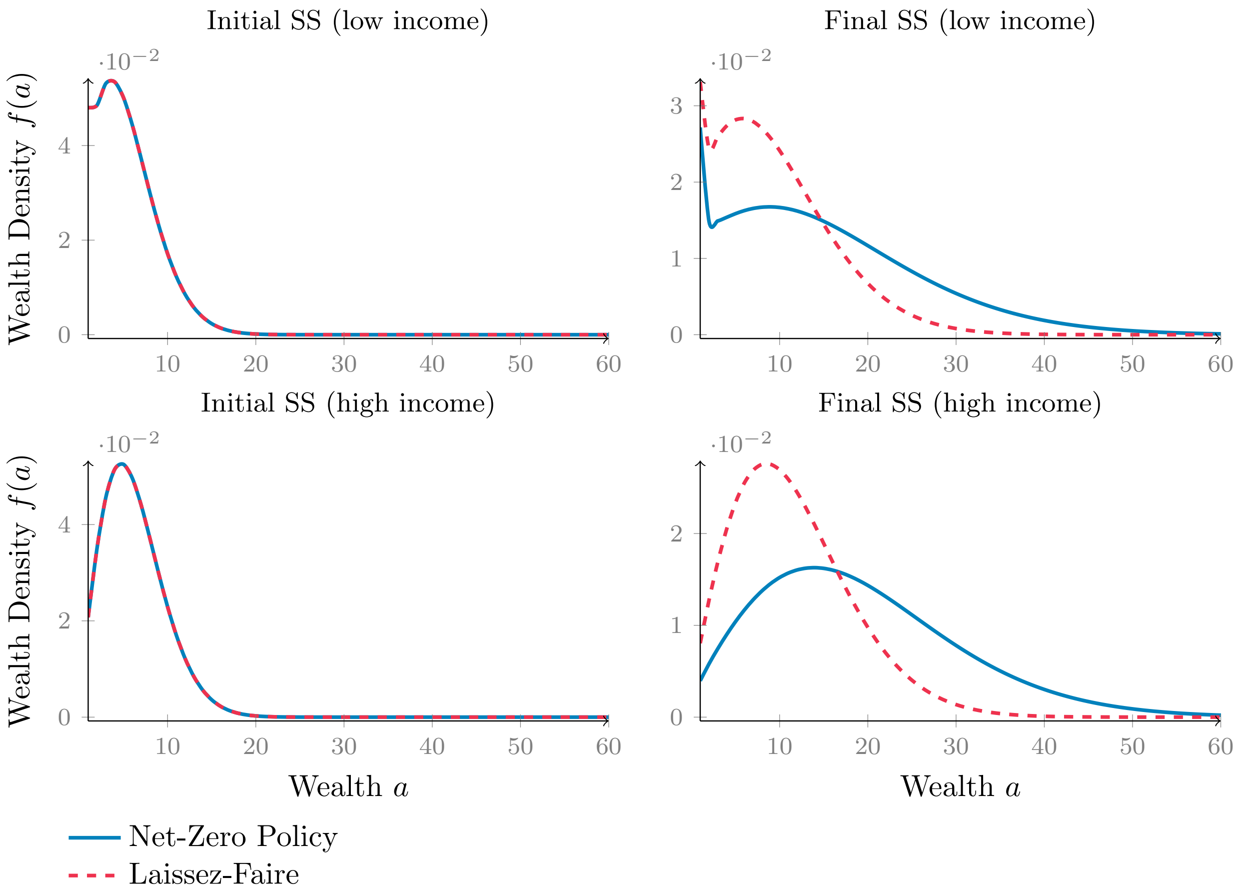
	Laissez-faire	Net-zero	% Change
Welfare	-5.4458	-3.5271	35.23%

Net-zero long-run distributional impacts

One main strength and advantage of our framework is its ability to investigate the social impacts of public policies such as a net-zero climate policy over the transition, which is not possible with RA models and not investigated with the climate carbon pricing HA models developed up to date (Bosetti and Maffezzoli [2013], Fried et al. [2018], Goulder et al. [2019], Cavalcanti et al. [2021], Fried et al. [2021], Känzig [2021], and Malafry and Brinca [2022]). These models do not feature distributional long-run transition pathways and mainly focus on steady state analysis or impulse responses.

When comparing the initial and final steady state value of the stationary distributions of wealth for high and low income households shown in figure XIV, engaging in a net-zero path reduces the distributional costs at the end of the transition in the economy as the distribution of wealth for both low and high earners shifts to the right (i.e. all household quantiles become wealthier compared to those in the laissez-faire scenario). This is largely due to the net-zero policy keeping temperature at levels below 2.2^{o}C, which ensures that temperature rise induced damages are not increasing overtime, which is otherwise the case under the laissez-faire scenario. Climate damages under the laissez-faire scenario rise to high levels following significant increases in temperature, which thus destroys capital and output, and in turn lowers the future realization of labour income and decreases consumption, leading to a higher level of distributional and welfare costs than with the net-zero case.

FIGURE XIV. Distributional Impacts of the Net-Zero Compared to the Laissez-faire



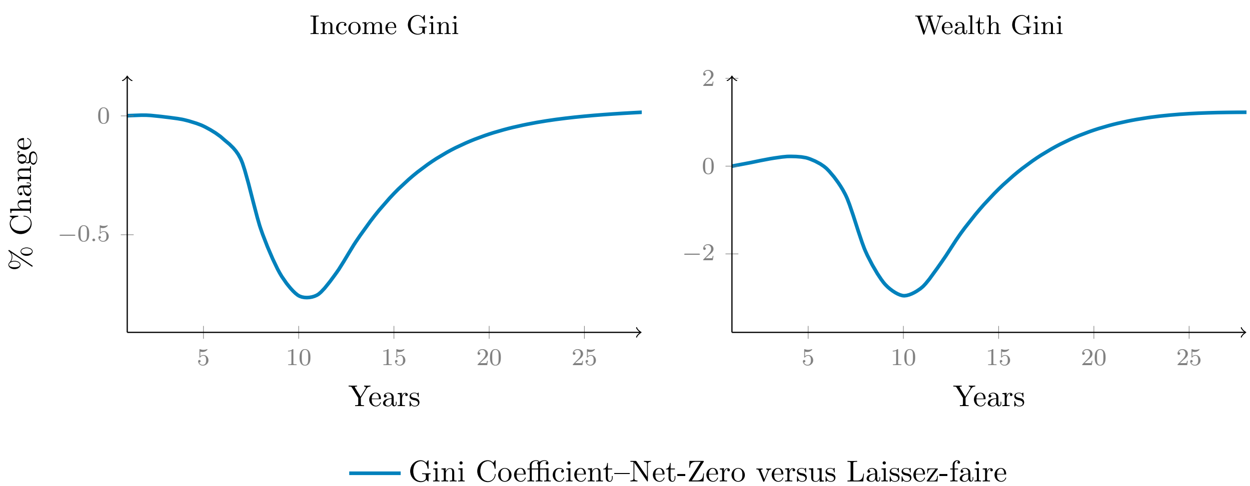
Note: This figure compares the net-zero scenario to a laissez-faire scenario at the initial and final steady state stationary wealth distributions for both low and high income households.

Net-zero short and medium-run distributional impacts

Focusing on a steady state analysis, however, is problematic when carbon prices are expected to rise over the transition to reach the net-zero objective. The political economy aspect of carbon pricing should not be underestimated when formulating public policy aimed at addressing the climate externality, as seen for example during the social upheaval in France with the *Gilets Jaunes*, whose extended protests were initially a reaction to a change in the carbon tax policy.

Looking at the Gini coefficients for both income and wealth[34] over the transition (2022-2050) as shown in figure XV, we find that inequalities decrease in the first 15 years of the transition by almost 1% and 2% for income and wealth, respectively, and that inequalities continue to be lower than 0 for the remaining 13 years of the transition (i.e. net-zero is equality enhancing compared to the laissez-faire scenario).

FIGURE XV. Income and Wealth Gini Coefficient Overtime: Net-Zero versus Laissez-faire



Note: This figure compares the net-zero scenario to a laissez-faire scenario for both the income and wealth Gini over the transition period.

One could be tempted to conclude that net-zero policy is able to improve the inequalities in income and wealth. However, when we turn to the household joint distributions of income and wealth, the picture is much more nuanced.

In figure XVI we present the wealth distribution transition pathways over the transition period 2022-2100. The left figure (a) shows how the distribution of wealth for low income is impacted over the transition to net-zero compared to the laissez-faire scenario, while figure (b) displays the results for high income earners.[35] At the beginning of the transition households expect higher output due to the announced 2 percent growth rate but also expect higher carbon prices as the government initializes the cap policy. As mentioned above, the growth expectation leads to an increase in consumption as household expect higher income

[34] As the Gini coefficient is often used as standard measure of inequalities.

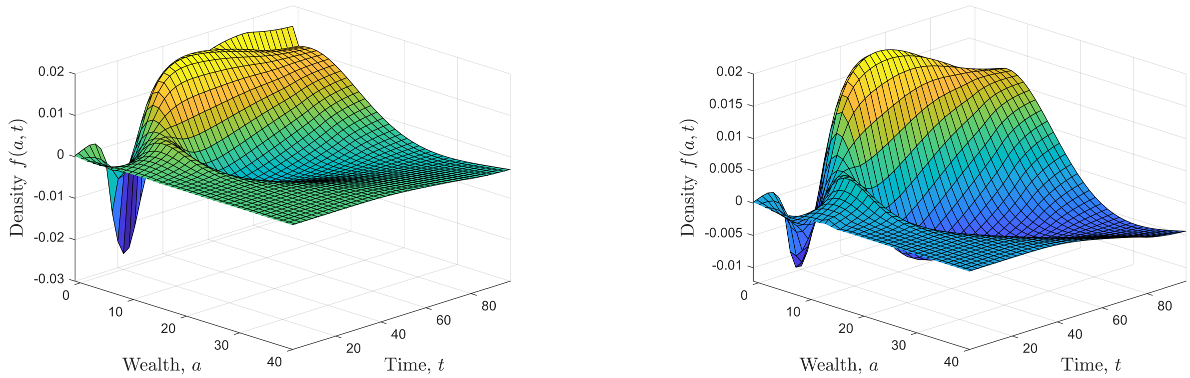
[35] We take the difference of the wealth distribution pathways between the net-zero and the laissez-faire

in the future. Furthermore, environmental policy sectoral targeting (starting with the energy sector) allows for a decrease capital losses during the period in which only the energy sector is emission caped. Intuitively, as the energy sector is smaller than the non-energy sectors in our economy, the growth expectation dynamics are stronger than the impacts of the rising carbon price expectation for the first 15-20 years. However, as soon the second phase of the cap policy is launched (in 2037), the percentage of households financially constraint wealth starts to rise (a considerable spike of about 5 percent and 3 percent in the case of moderate abatement costs in a period of less than 20 years is noted within low and high income earners, respectively)[36] as consumption is now directly impacted by the high carbon price that spans all economic sectors. Where the level impact of the carbon net-zero cap by 2050 is comparable between low and high income households with respect to the laissez-faire scenario (about 2 percent increase), the low income households remain the most impacted on aggregate. By substantially substituting toward higher consumption levels at the beginning of the transition, low income earners compared to high income earners, are of particular carbon prices rise concern.

For the remaining analysis, we will mainly focus on the joint distributions of income and wealth, rather than on the Gini coefficients, as the Gini suggests an improvement in inequalities, while the joint distributions show that all households are getting poorer (less wealthy) over the transition.

[36]In figure XXXIV, figure XXXV, and figure XXXVI, we present different transition of the wealth distribution for three levels of abatement efficiency cost. In the case of inefficient abatement scenario, the percentage of households financially constrained increase by about 10 percent when economic sectors are subject to emission cap.

FIGURE XVI. Net-Zero versus Laissez-faire with Moderate Abatement



(a) Low Income (b) High Income

Note: This figure compares the net-zero scenario to a laissez-faire scenario over the transition for the wealth distribution. Figure (a) show the household wealth pathway between 2022 and 2100 for low income households, while figure (b) displays the results for high income households. When a point is below zero that means the distribution of wealth across households has improved under the net-zero compared to laissez-faire and vice versa.

5.2.3 Net-Zero Transition Speed

Net-zero speed and transition pathways

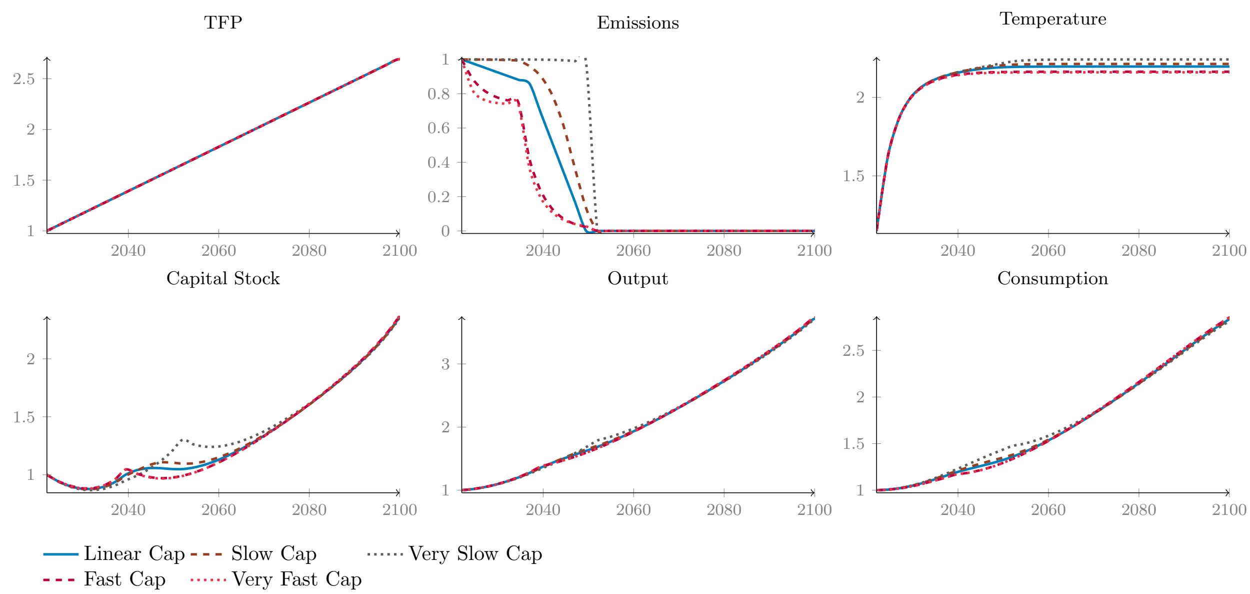
As discussed above, the lion's share of the climate literature focuses on the drivers and the level of social cost of carbon, which, in a decentralized equilibrium, corresponds to the optimal carbon price level. In an HA framework, defining the optimal carbon pricing (i.e. the social cost of carbon) is not straightforward, as it falls within the sphere of normativity. The level of optimal carbon pricing in an HA model will depend on the weight applied to the different agents' utilities. There is therefore a real need to identify a normative framework to be able to beging to answer the important question: what is the optimal carbon price in an HA framework?[37]

While identifying the optimal social cost of carbon requires first an agreement over the normative framework to be used, we investigate four different trajectories (concave and convex) in addition to our baseline linear carbon cap scenario. The four additional trajectories,

[37] Adrien Auclert (2022) discussion at the FED of New York. https://libertystreeteconomics.newyorkfed.org/2022/01/the-effect-of-inequality-on-the-transmission-of-monetary-and-fiscal-policy/.

which we refer to as fast, very fast, slow, and very slow allow us to attain a wide range of possible transition scenarios to net-zero.

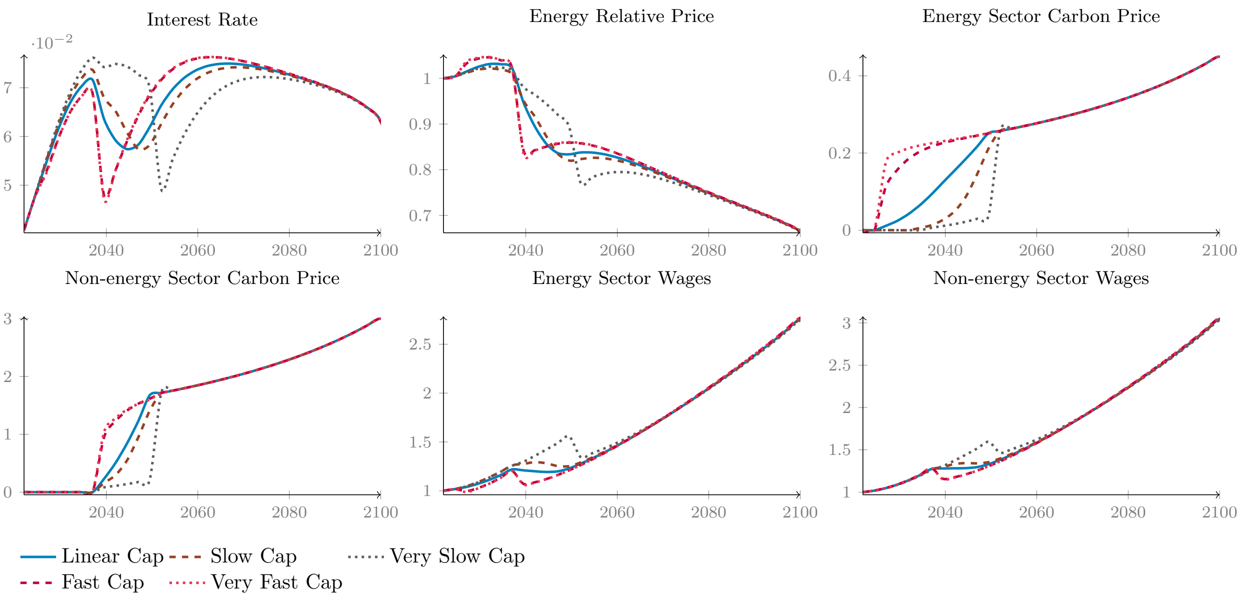
FIGURE XVII. Net-Zero Emission Target Trajectories – Macro Aggregates



Note: This figure compares five different net-zero trajectories: i) linear (baseline case), ii) fast cap, iii) very fast cap, iv) slow cap, and v) very slow cap.

Figure XVII presents the transition pathways for our economy's macro-aggregates. Acting promptly with aggressive environmental policies or, in contrast, delaying the intervention until the last minute, has little impact on the output over the transition period (2022-2100). However, acting today to reduce emissions to zero as opposed to acting 28 years from now would have consequences on the temperature level. While over the transition, the temperature variation is of a small magnitude, the inertia over the long-run would mean a small deviation today would lead to significant difference over the long-run (as we demonstrate and discuss above figure IX). The impact on consumption during the transition follows the pathway of capital movements. When the regulator decides to act fast, agents expect a sharp decrease in emissions, which requires major investment by firms. This triggers capital investment relocation toward higher investment in abatement costs. This substitution toward abatement investment is costly and thus leads to a lower level of capital (in the case of a fast cap compared to a slow cap), which in turn leads to a lower level of consumption and a rise in wealth losses (as shown in figure XLV, figure XLVI, figure XLII, and figure XLIII).

FIGURE XVIII. Net-Zero Emission Target Trajectories – Prices



Note: This figure compares five different net-zero trajectories: i) linear (baseline case), ii) fast cap, iii) very fast cap, iv) slow cap, and v) very slow cap.

With respect to prices, figure XVIII shows how the interest rate, energy price, and carbon prices, as well as wages are impacted following our four plus one (linear) policy speeds. Policy speed is shown to have a significant impact on the interest rate and the energy price, where the dips at the start of the environmental policy are rather strong compared to the case where the environmental cap is set linearly. This suggests potential volatility issues within financial markets that could lead to further consumption drops. Conducting a slow versus a fast cap has a significant impact on labor income (about 25-30 percent decrease when policy is conducted following a fast cap versus a slow cap). This is due to the sudden needs of abatement investment and reallocation of factors of production.

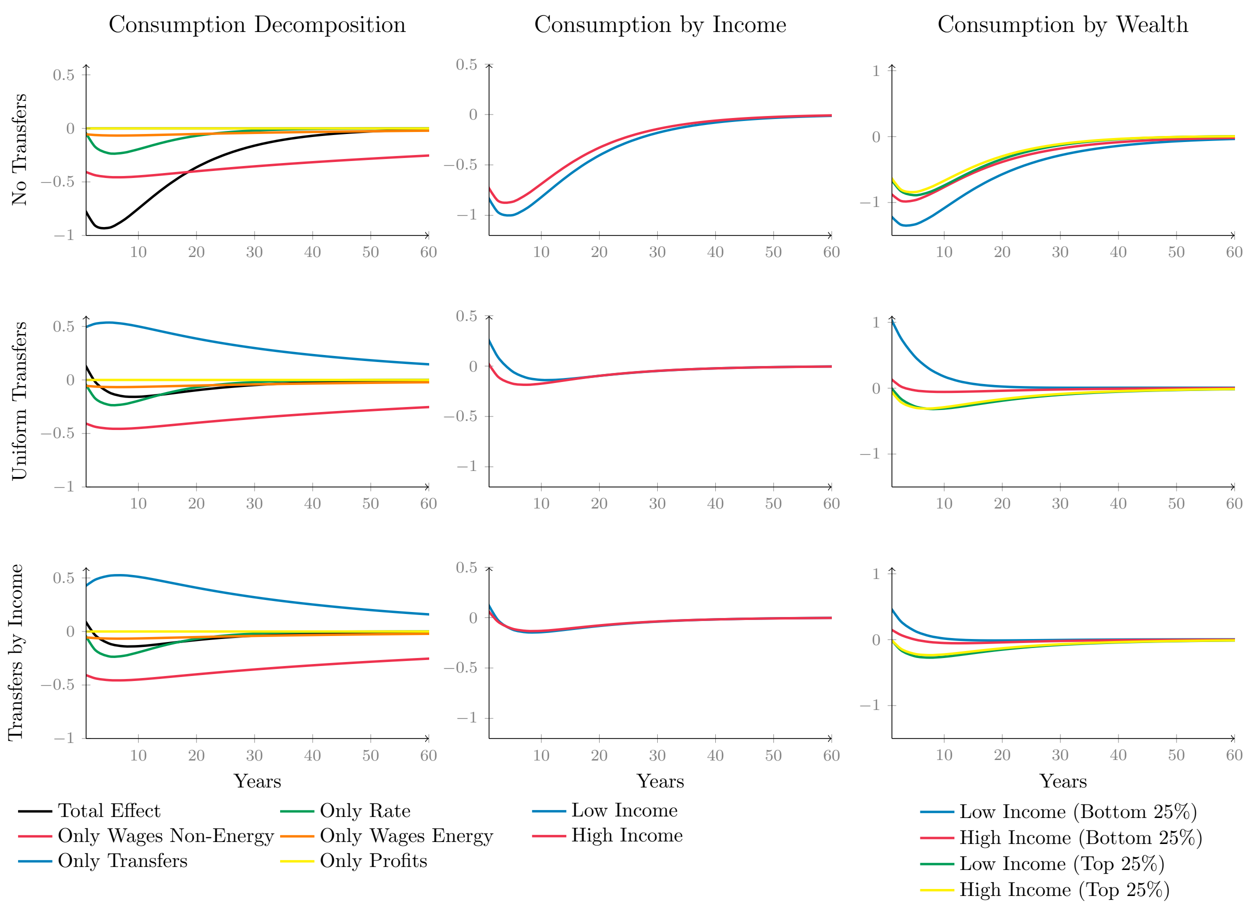
5.3 Redistribution of Carbon Revenues

As argued above, implementing carbon pricing consistent with the net-zero target is not a free lunch and leads to a rise in financially constrained and poor households over the transition period. In the following section we show how redistributing the carbon fiscal revenues could help smooth the net-zero transition and offset some of the negative effect.

5.3.1 Carbon Policy and Transfers

Figure XIX shows the impact on consumption decomposed into various indirect effects, by income and by wealth (as in section 5.1.4), according to the use made of carbon revenues. In the case where no transfer scheme is implemented by the government (first row in figure XIX), the proceeds from carbon taxation are used for unproductive government spending and this scenario corresponds to the first row in figure VIII.

FIGURE XIX. Fiscal Transfers and Consumption Drivers



Note: The figure plots the reaction of consumption according to three different fiscal transfer scenarios. The first row corresponds to the case with no fiscal transfers. The second row corresponds to the case with uniform fiscal transfers. And the last row corresponds to the case with per income fiscal transfers. The first column plots the reaction of consumption as well as its four components. The second column plots the reaction of consumption according to the realization of income. And the last column plots the reaction of consumption according to the realization of income and the level of wealth.

When the government decides to redistribute revenues uniformly (second row), it is able to completely offset the negative impact on consumption, for both low-income and high-income households. Moreover, uniform redistribution particularly benefits low-income households with little wealth. The reason is that these households do not earn much return on capital and/or profits, which implies that transfers represent a high share of their disposable income compared to other types of households. Therefore, low-income households with low wealth actually increase their consumption when the carbon price shock is combined with uniform redistribution of revenues. This result is consistent with Goulder et al. [2019], who show that recycling carbon proceeds can benefit lower income households and induce a progressive effect overall. Although this result may seem very promising, one should keep in mind that distorting the trade-off between consumption and savings may reduce the potential for future growth. If this type of redistribution policy prevents households from accumulating wealth, the long-run impact could ultimately be regressive. In that sense, income-based redistribution of carbon revenues is an attractive alternative, as it generates less volatility in consumption across income/wealth groups of households, while still offsetting the negative effect of carbon pricing exhibited in figure VIII.

Analysis of various recycling policies following an MIT carbon price shock shows that revenue redistributions, whether uniform or income-based, can offset most of the negative impact on consumption, and thus on welfare. These findings are in line with Malafry and Brinca [2022], who show that the optimal price of carbon is higher when the government engages in revenue redistribution. Keeping a long-run perspective in mind, however, this exercise implies that recycling carbon revenues by income would be less distortionary. To confirm this intuition, we now turn to the analysis of the distribution during the transition to net-zero.

5.3.2 Net-Zero Distributional Impacts and Transfers

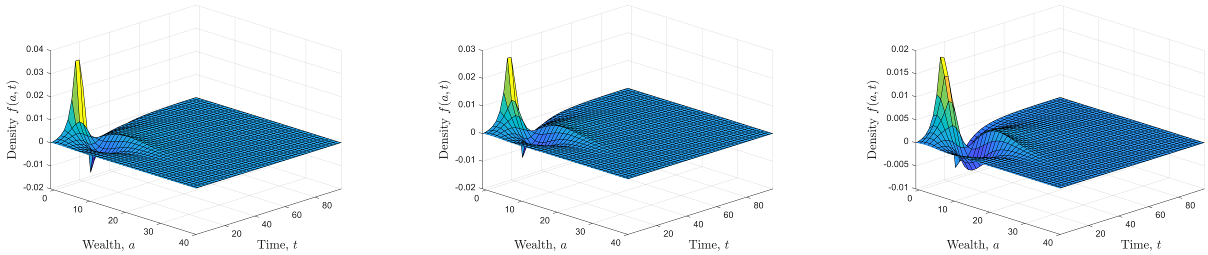
Figure XX and figure XXI compare the net-zero scenario distributed fiscal transfers (uniformly and by income) with the net-zero scenario without fiscal transfers, over the transition for the wealth distribution. When the density value is positive, this means that we have a negative impact on the wealth distribution and vice versa. In other words, when the density function is positive at a given point, this means that the distribution of households shifted toward the right.

Over the net-zero transition, redistributing carbon fiscal revenues to households, both uniformly and by income, allows for decreasing disparities between different household and over 2043 and 2050 (that is, when the second phase of the cap policy is engaged, which includes all other non-energy sectors). Focusing, however, on the first 20 years of the transition period, and as highlighted in the case of distributional impacts over the transition with no fiscal transfers (i.e. figure XVI results), both uniform and per income fiscal transfers allow household to engage in less precautionary savings to face the future impacts of the rising carbon costs, and thus achieve a higher consumption level. In other words, fiscal redistribution acts as a smoothing mechanism that reduces household saving incentives during the first 20 years, and boosts their consumption, which as shown allows for reducing the impacts on the wealth distribution (and welfare) compared to the case with no fiscal transfers between 2043 and 2050.

Between uniform and per income fiscal transfer, it appears (as it is also the case in the previous section) that per income transfers allow for the fewest spikes and the least change overtime.

We note that, although, fiscal transfers are able to offset some of the unequal impacts of carbon pricing, the medium/long run effect cannot be addressed solely by redistributing carbon revenues. Carbon proceeds after 2050 are equal to zero ($\tau_t E_t = 0$), and firms still engage in abatement investments to maintain emissions at zero. The distribution density function in figure XX and figure XXI which is between 40 and 80 (and corresponds to 2060 and 2102) is almost equal to zero (flat plane). This means that there is no difference between net-zero with or without fiscal transfers. In contrast, for example in figure XVI (which represents the net-zero scenario with no fiscal transfers compared to the laissez-faire scenario), we see that for the same period overall poverty (i.e. losses in capital holdings) rises. Thus, under fiscal transfers, distributional costs still rises. This last result is of special importance and suggests the need to investigate the ways by which abatement costs can be made cheaper.

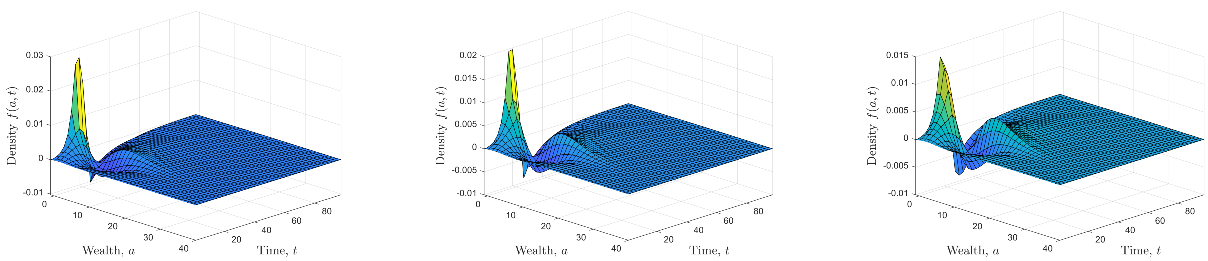
FIGURE XX. Net-Zero with Uniform Fiscal Transfers versus without Transfers – Medium Abatement Efficiency



(a) Low Income (b) Average Income (c) High Income

Note: This figure compares the net-zero scenario with uniformly distributed fiscal transfers to the net-zero scenario without fiscal transfers scenario over the transition for the wealth distribution. Figure (a) show the household wealth pathway between 2022 and 2100 for low income households, while figure (b) and figure (c) displays the results for average and high income households, respectively. When a point is below zero that means the distribution of wealth across households has improved under the net-zero with uniformly distributed fiscal transfers compared to net-zero without fiscal transfers and vice versa.

FIGURE XXI. Net-Zero with Fiscal Transfers (by Income) versus without Transfers – Medium Abatement Efficiency



(a) Low Income (b) Average Income (c) High Income

Note: This figure compares the net-zero scenario with per income distributed fiscal transfers to the net-zero scenario without fiscal transfers scenario over the transition for the wealth distribution. Figure (a) show the household wealth pathway between 2022 and 2100 for low income households, while figure (b) and figure (c) displays the results for average and high income households, respectively. When a point is below zero that means the distribution of wealth across households has improved under the net-zero with per income distributed fiscal transfers compared to net-zero without fiscal transfers and vice versa.

6 What About Inflation And Carbon Pricing?

6.1 Case of Sticky Prices (HANK): Model Changes

Firms

In the case of sticky prices, monopolistic non-energy firms engage in a price setting à la Rotemberg [1982]. Price update is subject to a quadratic adjustment in the rate of price change and is expressed as a fraction of aggregate output:

$$\Delta_{j,t}^P = \frac{\theta^P}{2}\left(\frac{\dot{p}_{j,t}}{p_{j,t}}\right)^2 Y_t. \tag{60}$$

For the ease of reading and as firms are identical, we suppress notational dependence on j. Thus, profit maximization subject to the demand from final firms yields the New Philips Curve[38]:

$$\left(r_t^a - \frac{\dot{Y}_t}{Y_t}\right)\pi_t = \frac{\theta}{\theta^P}(mc_t - mc^*) + \dot{\pi}_t \tag{61}$$

where, $mc^* = \frac{\theta-1}{\theta}$, and π_t is the inflation rate.

The flow profits before price adjustment is similar to the RBC case, as such the flow profits in the case of sticky prices will include the price adjustment costs:

$$\Pi_t^F = (1 - mc_t)Y_t - \frac{\theta^P}{2}{\pi_t}^2 Y_t. \tag{62}$$

The Monetary Authority

Under the presence of price stickiness (i.e. the non-neutrality of monetary policy), the central bank follows a simple Taylor [1993] rule to set the nominal interest rates i_t^i:

$$i_t^i = \bar{r}^a + \phi_\pi \pi_t + \phi_Y(Y_t - \bar{Y}) \tag{63}$$

where $\bar{r}^a$ is the steady state of real rate and $\phi_\pi \geq 1$ is the inflation stance. $\bar{Y}$ is the steady state level of output, while ϕ_Y is the central bank reaction to output gap.

In addition, the relationship between the nominal and the real interest is modeled through the Fisherian equation:

$$i_t^i = r_t^a + \pi_t \tag{64}$$

[38] The full derivation can be found in the appendix section C.2.

6.2 Solution Method

In the presence of price stickiness, the updating iterative algorithm rule does not allow for convergence when used to clear the New Phillips Curve. We instead rely on the system of equations method to solve the transition dynamics for the marginal cost:

$$\mathrm{MC}(k_1^*, ..., k_N^*) = 0 \tag{65}$$

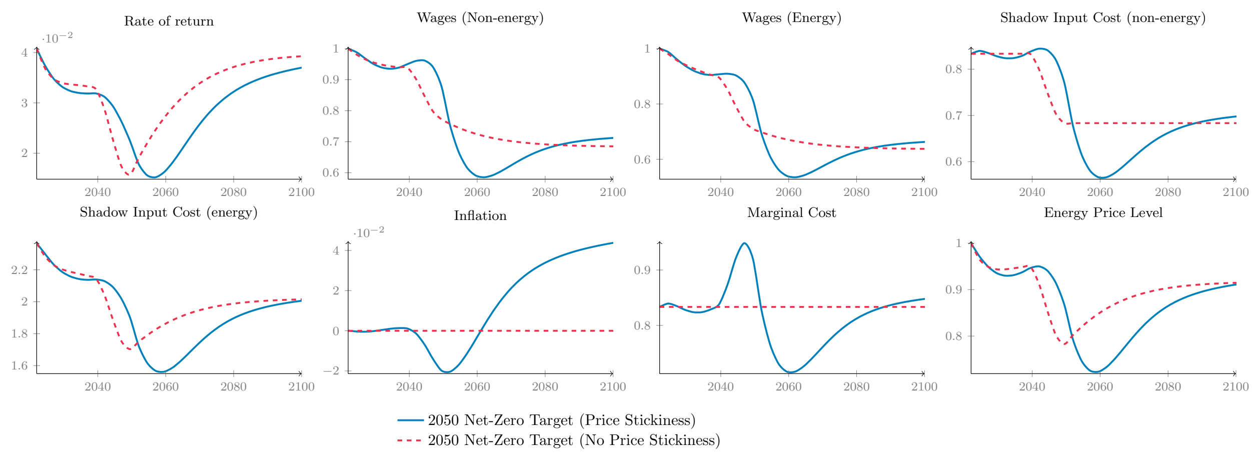
where MC: $\mathbb{R}^N \rightarrow \mathbb{R}^N$ denotes the N-period excess marginal cost function.

6.3 Results

Under the presence of price rigidities, the marginal cost for firms is subject to fluctuations. To understand the implications of the net-zero emissions target and its interaction with inflation, we simulate a transition pathway consistent with the net-zero emissions target under a linear cap, and with by income fiscal transfers and no TFP growth. Figure XXII shows the cases both of sticky prices (in blue) and flexible prices (in red) where inflation has no role.

Over the net-zero transition (i.e. 2022-2050), the high cost of offsetting carbon emissions pushes firms to decrease wages, which in turn pushes the input shadow costs downward, thus decreasing inflationary pressures. This, however, is not the case in the first few years (i.e. until 2038), whereby households perfectly foresee the high cost of the environmental transition and engage in precautionary savings. This response allows for the level of capital to remain close to that of the case of flexible prices, and ultimately keeps inflation stable, as the shadow input costs and marginal costs remain stable. Thereafter (once the transition to net-zero has been accomplished, i.e. after 2050), inflationary pressures kick in, as both wages and rates of return rise given that the tax revenue becomes zero, which increases the shadow input costs. While inflation could be less of a concern over the transition, the long-run consequences could see inflation rise to over 5 percent by 2080. This could be of major concern to the conduction of monetary policy. However, we recognize that modeling choices are paramount to these results, and further research should investigate the inflationary pressures over the transition, using a full two asset modeling framework à la Kaplan et al. [2018].

FIGURE XXII. Inflation and Net-Zero Target Interactions



Note: The figure plots the reaction of relevant macro-aggregates and prices according to two modeling choices: i) in blue the presence of price stickiness, and ii) in red under the assumption of flexible prices. In both cases, we plot the net-zero trajectory under no TFP growth.

7 Learning By Doing and Abatement Efficiency

7.1 Model Changes

In this section we highlight the role of green innovation. The cost function of abatement is now steered by endogenous green innovations:

$$f(\mu_t^s) = \left(\int_0^{A_t^g} f(\mu_{j,t}^s)^{\frac{1}{\theta_3}} dj \right)^{\theta_3}, \tag{66}$$

Thus,

$$f(\mu_t^s) = \theta_1 (\mu_t^s)^{\theta_2} (A_t^g)^{-\theta_3} \tag{67}$$

where $\theta_3 > 0$ is the elasticity of green innovations[39] and s the two sectors in our economy (i..e energy and non-energy sectors).

Where one could model green innovations A_t^g with an endogenous growth process as in Benmir and Roman [2021], we use abatement level μ_t as a learning indicator. This reduced

[39] We conduct sensitivity analysis over different values of θ_3.

form allow for capturing the learning by doing, without necessarily worrying about the sources of green innovation funding. As such, the abatement cost function reads as:

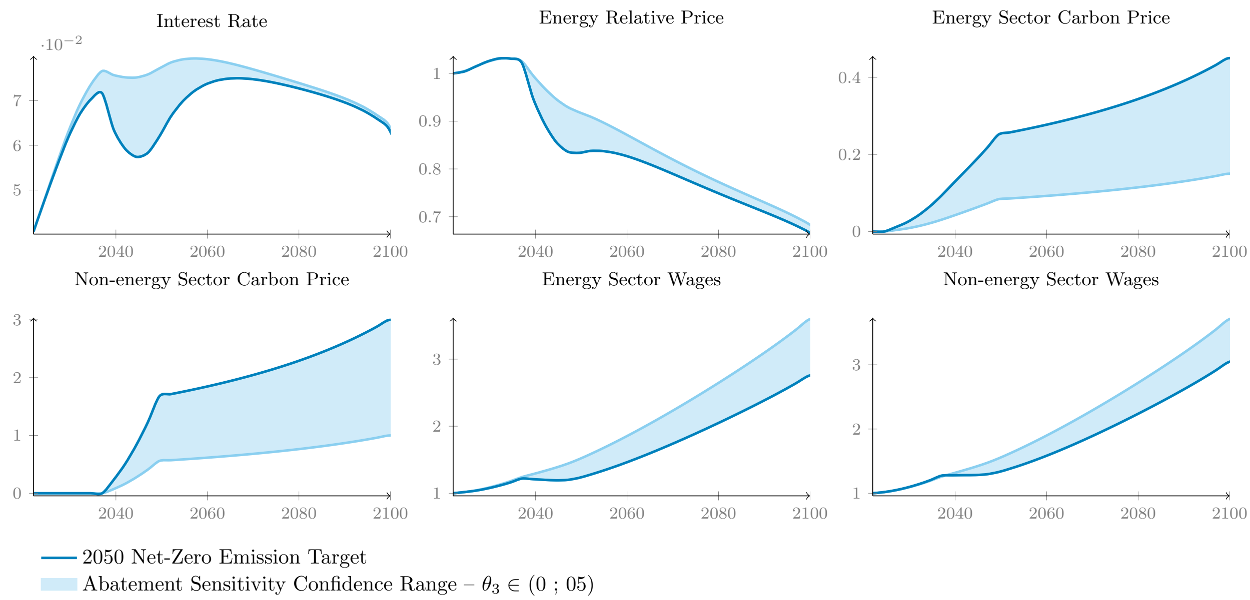
$$f(\mu_t^s) = \theta_1 (\mu_t^s)^{\theta_2 - \theta_3} \tag{68}$$

7.2 Results

Figure XXII shows how accounting for learning by doing within abatement costs, allows for a smoother transition as carbon price costs decrease over the transition, thus allowing for higher wages and rates of returns. This in turn stimulates the economy and would decrease distributional impacts stemming from the net-zero transition.

Intuitively, with green innovation decreasing abatement investment costs, firms do not need to engage in costly resource reallocation, where they decrease both their capital holdings and labor wages. Instead, firms are able to make cheap investments in abatement technologies as the cost is low, which ultimately maintains the shadow input cost levels close to the laissez-faire scenario. In such a case, the impacts on the distribution are less pronounced and the net-zero transition is less costly for households and firms alike, as both capital holdings and wages remain high in the economy.

FIGURE XXIII. Abatement Learning By Doing and Macro Prices



Note: The figure plots the relevant macro-prices according to two modeling choices: i) in tick blue the baseline abatement intensity, and ii) in shaded blue a range of values for learning intensity. In both cases, we plot the net-zero trajectory under 2 percent TFP growth.

8 Conclusion

In this paper, we provide a framework to study the effects of the transition to a low-carbon economy on household income and wealth distribution.

We first conduct an empirical analysis of the California carbon cap-and-trade market to investigate the propagation channels and impacts of carbon price shocks on Californian households, and do so using U.S. climate Sentometric data. We show how California carbon pricing shocks increase energy prices and decrease net-energy generation, which decreases wages and momentarily increases equity returns before the latter decreases over time. Furthermore, when focusing on household bottom and top income quantiles, the carbon price shock is found to impact households asymmetrically depending on their level of income. In particular, we find that the bottom 50 percent income level households see their consumption fall, while a positive shock on the price of carbon tends to momentarily increase consumption for the top 50 percent income level households. We conduct a series of sensitivity checks, which indicate that the results are robust along a number of dimensions including the selection of news, the estimation technique, the model specification, and the sample period.

We then develop a heterogeneous household model with two production sectors: i) an energy sector and ii) a non-energy sector. We first use the model to decompose the effect of a carbon price shock on households, before assessing the impact of the net-zero target on aggregate variables and the distribution. Much of the transmission of a shock on the price of carbon goes through wages and the interest rate. As such, implementing carbon taxation in the energy sector or in the non-energy sector leads to different outcomes. We find that it is overall less costly to first abate emissions in the energy sector, consistent with policies implemented in the EU and in California. Furthermore, putting a price on carbon in the non-energy sector has higher impacts in terms of distributional costs on consumption and wealth. These findings are confirmed by the study of the transition dynamics to net-zero. Although we show that acting to lower emissions is required to avoid major economic losses on a long-run horizon, distributional and welfare costs are expected to rise in the short run. To mitigate the rapid changes in the distribution of wealth over the transition, we investigate the role of transfers. Income-based redistribution of carbon revenues proves to be the most effective in smoothing household consumption and savings decisions during the uncertain emissions reduction period.

Overall, the findings of this paper suggest that while the transition to net-zero is a necessary step toward a long-run sustainable economy, it induces changes in the distribution of income and wealth that could potentially lead to social unrest. Public authorities need to anticipate and monitor the impact of large-scale environmental policies on different types of households (especially financially-constrained households) if the transition is to be successful. In this perspective, targeted redistribution of carbon revenues could be a major tool in government strategies. We note that, although fiscal transfers are able to offset some of the unequal impacts of carbon pricing, the medium/long run effect cannot be addressed solely by redistributing carbon revenues. Additionally, the need for cheaper abatement technologies is paramount. To this extent, we consider the case of abatement learning and show how fiscal redistribution and green innovation decreases carbon prices and boosts consumption over the transition. Finally, turning to the linkages between inflation and carbon pricing, we show that net-zero carbon pricing costs induce inflationary pressure over the long run, thus suggesting a potential challenge for monetary policy in so far as keeping inflation under the desired target.

9 Bibliography

D. Acemoglu, P. Aghion, L. Bursztyn, and D. Hemous. The environment and directed technical change. *American economic review*, 102(1):131–66, 2012. 7

D. Acemoglu, D. Hemous, L. Barrage, P. Aghion, et al. Climate change, directed innovation, and energy transition: The long-run consequences of the shale gas revolution. In *2019 Meeting Papers*, number 1302. Society for Economic Dynamics, 2019. 7

Y. Achdou, J. Han, J.-M. Lasry, P.-L. Lions, and B. Moll. Income and wealth distribution in macroeconomics: A continuous-time approach. *The review of economic studies*, 89(1): 45–86, 2022. 6, 8, 21, 32, 35

P. Aghion, A. Dechezleprêtre, D. Hemous, R. Martin, and J. Van Reenen. Carbon taxes, path dependency, and directed technical change: Evidence from the auto industry. *Journal of Political Economy*, 124(1):1–51, 2016. 7

S. Ahn, G. Kaplan, B. Moll, T. Winberry, and C. Wolf. When inequality matters for macro and macro matters for inequality. *NBER macroeconomics annual*, 32(1):1–75, 2018. 8, 29

S. R. Aiyagari. Uninsured idiosyncratic risk and aggregate saving. *The Quarterly Journal of Economics*, 109(3):659–684, 1994. 6, 35

D. Ardia, K. Bluteau, K. Boudt, and K. Inghelbrecht. Climate change concerns and the performance of green versus brown stocks. *National Bank of Belgium, Working Paper Research*, 2(1):229–260, 2020. 4, 8, 9, 10, 78

A. Auclert. Monetary policy and the redistribution channel. *American Economic Review*, 109(6):2333–67, 2019. 8, 42

A. Auclert, B. Bardóczy, M. Rognlie, and L. Straub. Using the sequence-space jacobian to solve and estimate heterogeneous-agent models. *Econometrica*, 89(5):2375–2408, 2021. 8

L. A. Bakkensen and L. Barrage. Going underwater? flood risk belief heterogeneity and coastal home price dynamics. *The Review of Financial Studies*, 2021. 7

M. Barnett, W. Brock, and L. P. Hansen. Pricing uncertainty induced by climate change. *The Review of Financial Studies*, 33(3):1024–1066, 2020. 6

G. Benmir and J. Roman. *Policy interactions and the transition to clean technology*. Grantham Research Institute on Climate Change and the Environment, 2020. 7, 26, 50

G. Benmir and J. Roman. Endogenous abatement technology. 2021. 67

J.-T. Bernard and M. Kichian. The impact of a revenue-neutral carbon tax on gdp dynamics: The case of british columbia. *The Energy Journal*, 42(3), 2021. 8

T. Boppart, P. Krusell, and K. Mitman. Exploiting mit shocks in heterogeneous-agent economies: the impulse response as a numerical derivative. *Journal of Economic Dynamics and Control*, 89:68–92, 2018. 8

V. Bosetti and M. Maffezzoli. Taxing carbon under market incompleteness. 2013. 7, 53

M. Burke, S. M. Hsiang, and E. Miguel. Global non-linear effect of temperature on economic production. *Nature*, 527(7577):235–239, 2015. 6

J. B. Bushnell, H. Chong, and E. T. Mansur. Profiting from regulation: Evidence from the european carbon market. *American Economic Journal: Economic Policy*, 5(4):78–106, 2013. 8

Y. Cai and T. S. Lontzek. The social cost of carbon with economic and climate risks. *Journal of Political Economy*, 127(6):2684–2734, 2019. 6, 22, 46, 50, 95

T. Cavalcanti, Z. Hasna, and C. Santos. Climate change mitigation policies: Aggregate and distributional effects. 2021. 7, 53

R. Colacito, B. Hoffmann, and T. Phan. Temperatures and growth: A panel analysis of the united states. *Journal of Money, Credit, and Banking*, 51(2-3):2019, 2018. 6

M. Dell, B. F. Jones, and B. A. Olken. Temperature shocks and economic growth: Evidence from the last half century. *American Economic Journal: Macroeconomics*, 4(3):66–95, 2012. 6

W. J. Den Haan. Solving dynamic models with aggregate shocks and heterogeneous agents. *Macroeconomic dynamics*, 1(2):355–386, 1997. 8

C. Di Maria and S. Valente. Hicks meets hotelling: the direction of technical change in capital–resource economies. *Environment and Development Economics*, 13(6):691–717, 2008. 7

S. Dietz and N. Stern. Endogenous growth, convexity of damage and climate risk: how nordhaus' framework supports deep cuts in carbon emissions. *The Economic Journal*, 125 (583):574–620, 2015. 6, 37

S. Dietz and F. Venmans. Cumulative carbon emissions and economic policy: in search of general principles. *Journal of Environmental Economics and Management*, 96:108–129, 2019. 21, 22, 37, 50

S. Fried, K. Novan, and W. B. Peterman. The distributional effects of a carbon tax on current and future generations. *Review of Economic Dynamics*, 30:30–46, 2018. 7, 53

S. Fried, K. M. Novan, and W. Peterman. Recycling carbon tax revenue to maximize welfare. 2021. 7, 53

M. Gertler and P. Karadi. Monetary policy surprises, credit costs, and economic activity. *American Economic Journal: Macroeconomics*, 7(1):44–76, 2015. 4, 9, 11

M. Golosov, J. Hassler, P. Krusell, and A. Tsyvinski. Optimal taxes on fossil fuel in general equilibrium. *Econometrica*, 82(1):41–88, 2014. 21, 24, 50

L. H. Goulder, M. A. Hafstead, G. Kim, and X. Long. Impacts of a carbon tax across us household income groups: What are the equity-efficiency trade-offs? *Journal of Public Economics*, 175:44–64, 2019. 7, 53, 61

A. Grimaud and L. Rouge. Environment, directed technical change and economic policy. *Environmental and Resource Economics*, 41(4):439–463, 2008. 7

A. Imrohoroğlu. Cost of business cycles with indivisibilities and liquidity constraints. *Journal of Political economy*, 97(6):1364–1383, 1989. 5

D. R. Känzig. The economic consequences of putting a price on carbon. *Available at SSRN 3786030*, 2021. 4, 8, 19, 53

G. Kaplan, B. Moll, and G. L. Violante. Monetary policy according to hank. *American Economic Review*, 108(3):697–743, 2018. 21, 36, 42, 67

P. Krusell and A. A. Smith, Jr. Income and wealth heterogeneity in the macroeconomy. *Journal of political Economy*, 106(5):867–896, 1998. 8

K. N. Kuttner. Monetary policy surprises and interest rates: Evidence from the fed funds futures market. *Journal of monetary economics*, 47(3):523–544, 2001. 9

J.-M. Lasry and P.-L. Lions. Mean field games. *Japanese journal of mathematics*, 2(1): 229–260, 2007. 6

L. Malafry and P. Brinca. Climate policy in an unequal world: Assessing the cost of risk on vulnerable households. *Ecological Economics*, 194:107309, 2022. 7, 43, 53, 62

M. Mansanet-Bataller and A. Pardo. Impacts of regulatory announcements on co2 prices. *The Journal of Energy Markets*, 2(2):1–33, 2009. 8

A. McKay, E. Nakamura, and J. Steinsson. The power of forward guidance revisited. *American Economic Review*, 106(10):3133–58, 2016. 21

G. E. Metcalf. On the economics of a carbon tax for the united states. *Brookings Papers on Economic Activity*, 2019(1):405–484, 2019. 8

J. L. Montiel Olea, J. H. Stock, M. W. Watson, et al. Inference in structural vector autoregressions identified with an external instrument. *Journal of Econometrics*, 225(1):74–87, 2021. 4, 13, 15

E. Nakamura and J. Steinsson. High-frequency identification of monetary non-neutrality: the information effect. *The Quarterly Journal of Economics*, 133(3):1283–1330, 2018. 9

W. Nordhaus. A question of balance: Weighing the options on global warming policies. *Yale University Press, New Haven, CT*, 2008. 24, 37

W. D. Nordhaus. To slow or not to slow: the economics of the greenhouse effect. *The economic journal*, 101(407):920–937, 1991. 6, 22

W. D. Nordhaus and A. Moffat. A survey of global impacts of climate change: replication, survey methods, and a statistical analysis. *NBER Working Paper*, 2017. 37

V. A. Ramey. Macroeconomic shocks and their propagation. *Handbook of macroeconomics*, 2:71–162, 2016. 13

M. Reiter. Solving heterogeneous-agent models by projection and perturbation. *Journal of Economic Dynamics and Control*, 33(3):649–665, 2009. 8

J. J. Rotemberg. Sticky Prices in the United States. *Journal of Political Economy*, 90(6): 1187–1211, 1982. 65

I. Rudik, G. Lyn, W. Tan, A. Ortiz-Bobea, et al. Heterogeneity and market adaptation to climate change in dynamic-spatial equilibrium. Technical report, Iowa State University, Department of Economics, 2021. 6

A. F. Shapiro and G. E. Metcalf. The macroeconomic effects of a carbon tax to meet the us paris agreement target: The role of firm creation and technology adoption. Technical report, National Bureau of Economic Research, 2021. 8

C. A. Sims, J. H. Stock, and M. W. Watson. Inference in linear time series models with some unit roots. *Econometrica: Journal of the Econometric Society*, pages 113–144, 1990. 15

S. Smulders and M. De Nooij. The impact of energy conservation on technology and economic growth. *Resource and Energy Economics*, 25(1):59–79, 2003. 7

N. Stern. The economics of climate change. *American Economic Review*, 98(2):1–37, 2008. 6

J. B. Taylor. Discretion versus policy rules in practice. *Carnegie-Rochester Conference Series on Public Policy*, 39(1):195–214, December 1993. 65

C. P. Traeger. Uncertainty in the analytic climate economy. *CEPR Discussion Paper No. DP16065*, 2021. 7, 46

T. S. Van den Bremer and F. Van der Ploeg. The risk-adjusted carbon price. *American Economic Review*, 111(9):2782–2810, 2021. 46

R. Van der Ploeg, C. Hambel, and H. Kraft. Asset pricing and decarbonization: Diversification versus climate action. *University of Oxford Working Paper*, 2020. 6

M. L. Weitzman. Ghg targets as insurance against catastrophic climate damages. *Journal of Public Economic Theory*, 14(2):221–244, 2012. 6, 37

A Appendix: A

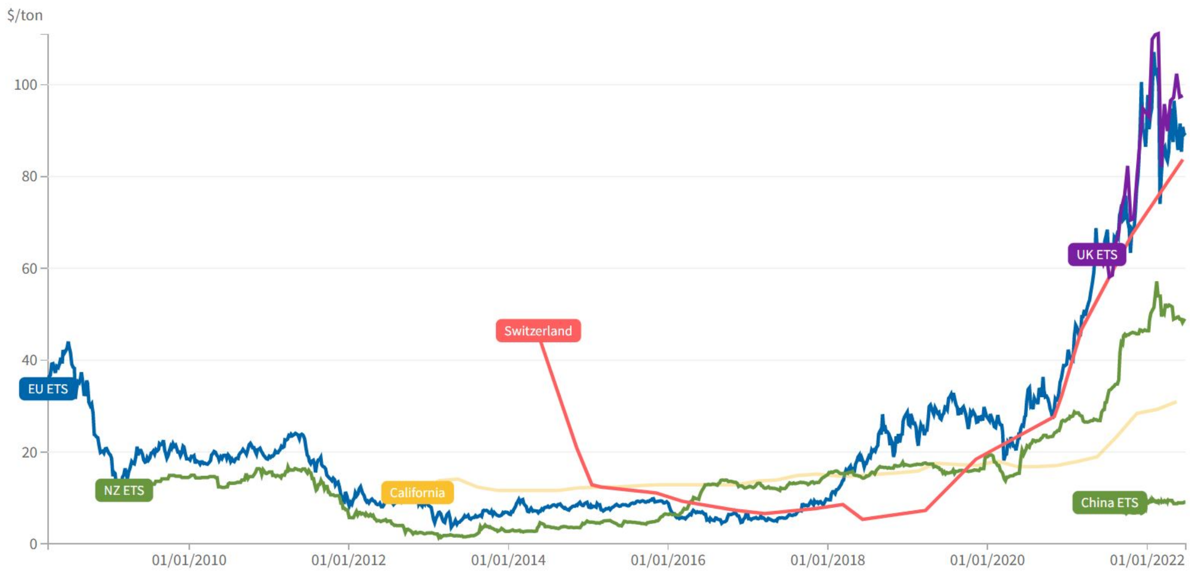
A.1 Data

The data used[40] in this section were obtained from following sources:

- U.S. climate sentiment data were extracted from the Sentometric data source, (Ardia et al. [2020]),
- California carbon futures prices data are obtained from Climate Policy Initiative database,
- California daily energy prices are taken from California Independent System Operator (California ISO) database,
- California net energy generation monthly data are taken from U.S. Energy Information Administration (EIA) database,
- California monthly data wages are obtained from the U.S. Bureau of Labor Statistics (BLS) database,
- California monthly equity returns index is received from Bloomberg,
- California quarterly consumption data by income quartile are constructed using CES collected by BLS,
- All other U.S. macro data (mainly used for model Calibration purposes) are obtained through Fred database.

[40] All data used were either for the heterogenous impact of carbon pricing on households (i.e. second IV-SVAR on consumption qunatiles) were extracted directly on a quarterly basis (CES data) or transformed from a daily frequency to a quarterly frequency (california energy composite prices and sentometric data). Similarly for all the other empirical regression, data were extracted on a monthly basis except data on energy prices and sentometric data.

FIGURE XXIV. Carbon Prices In the World's Major Cap-and-Trade Markets

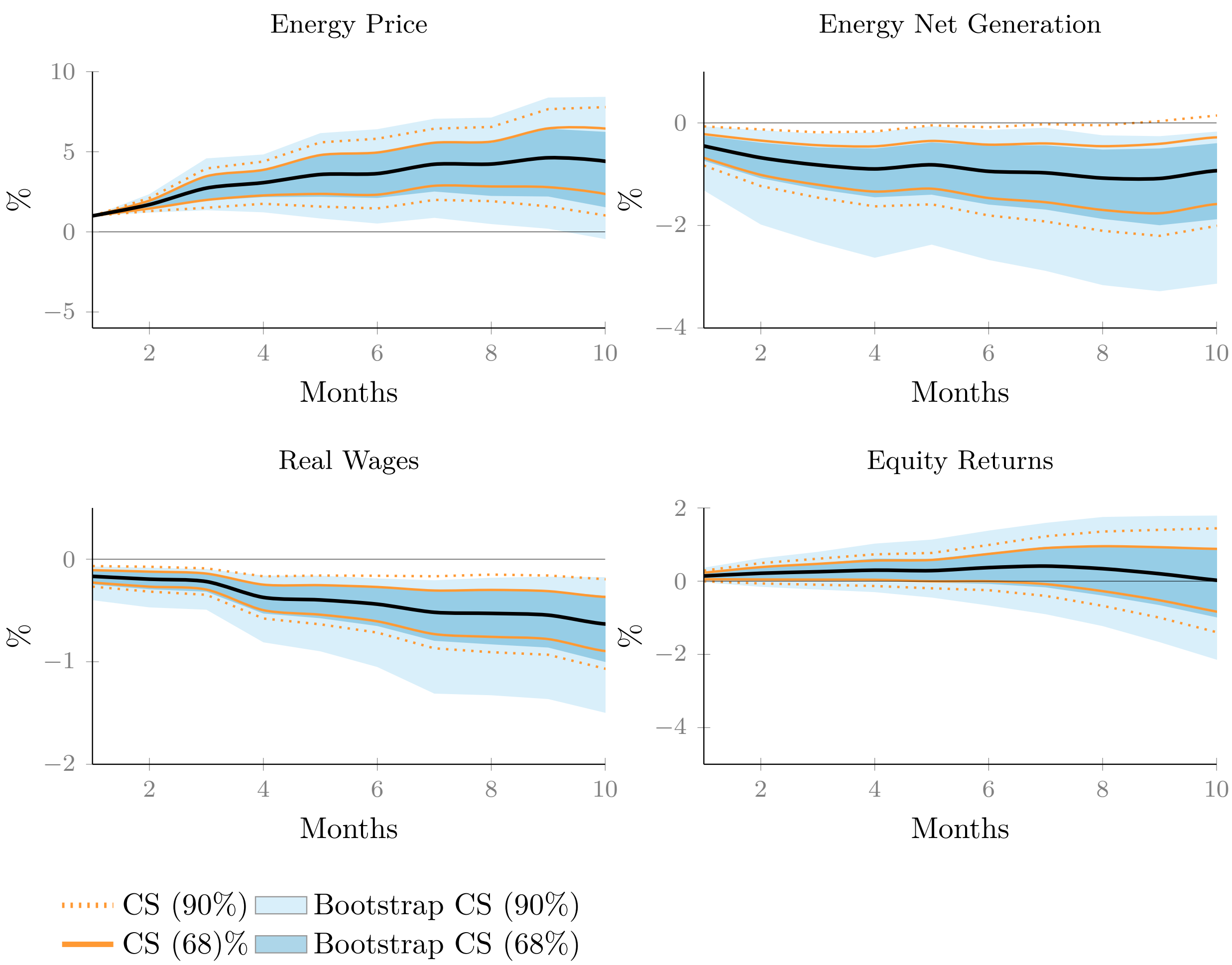


Note: The figure presents the carbon prices in major cap-and-trade world markets and is constructed using data from the International Carbon Action Partnership: https://icapcarbonaction.com.

A.2 IV-SVAR Robustness

Figure XXV presents the results when we exclude all days with no news. The results remain robust to including no climate news days (i.e. days with zero or unknown news about climate).

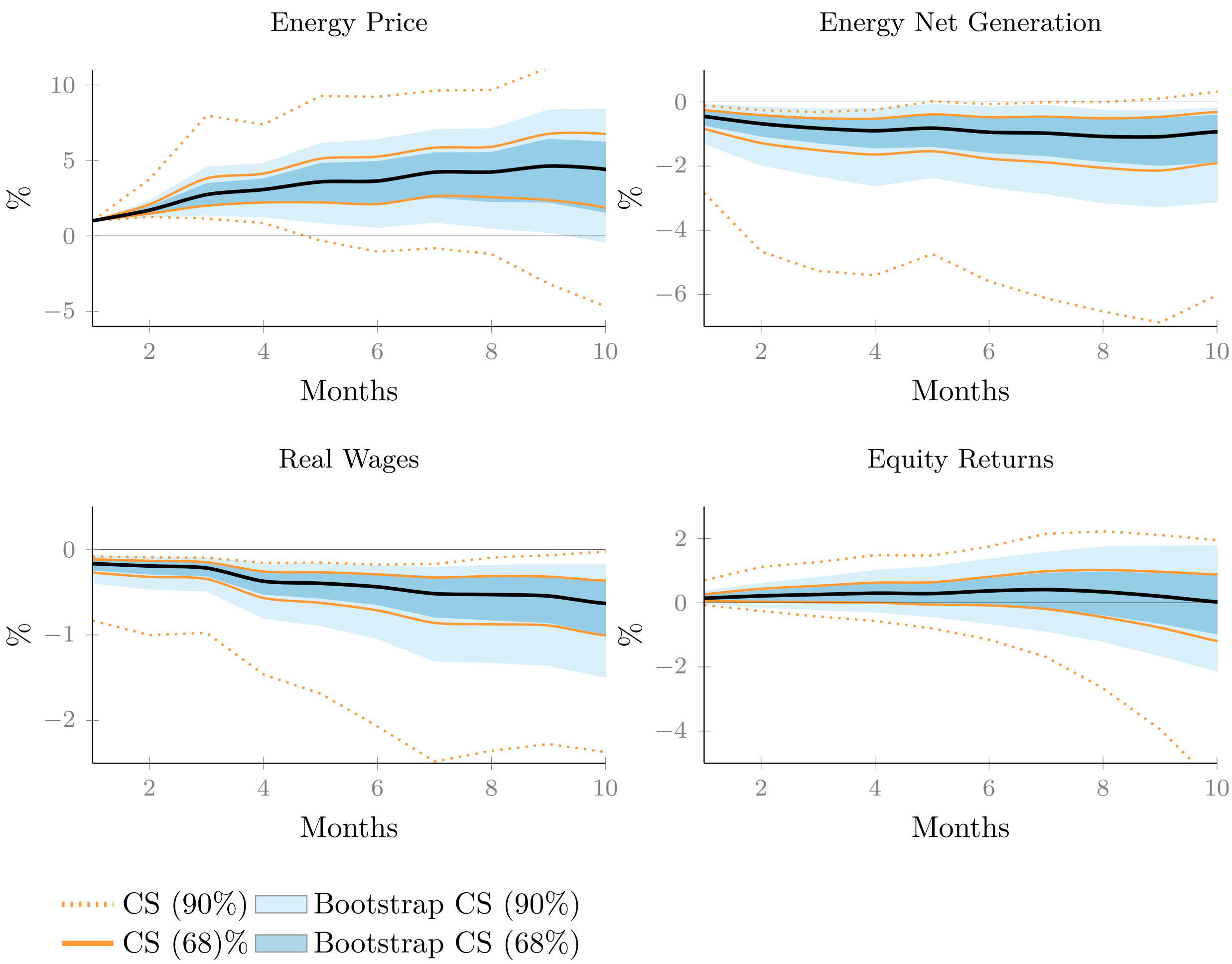
FIGURE XXV. IV-SVAR



Note: The figure presents the cumulative impulse responses to California carbon price market shocks, where we normalize the impact of the carbon shock to one percent on impact. In blue, we show the 68 and 90 percent confidence bands, while in orange we present the 68 and 90 percent confidence bands using bootstrapping procedure. In this robustness exercise, the carbon shock is constructed excluding all days with zero or no news.

Figure XXVI presents the results when we exclude all days with no news under weak IV robust inference specification. The results remain robust to including no climate news days (i.e. days with zero or unknown news about climate).

FIGURE XXVI. Weak IV-SVAR



Note: The figure presents the cumulative impulse responses to California carbon price market shocks, where we normalize the impact of the carbon shock to one percent on impact. In blue, we show the 68 and 90 percent confidence bands, while in orange we present the 68 and 90 percent confidence bands using bootstrapping procedure. In this robustness exercise, the carbon shock is constructed excluding all days with zero or no news. The inference is conducted using weak IV robust bootstrapping.

A.3 SVAR Model

In this section we present the structural vector auto-regressive model (SVAR), where the policy shock is used as a direct measure. The estimated SVAR reads as:

$$AY_t = \sum_{s=1}^{4} B_s Y_{t-s} + C\epsilon_t \tag{69}$$

where variables are ranked in the following order and the following imposed restriction on the structural matrix A:

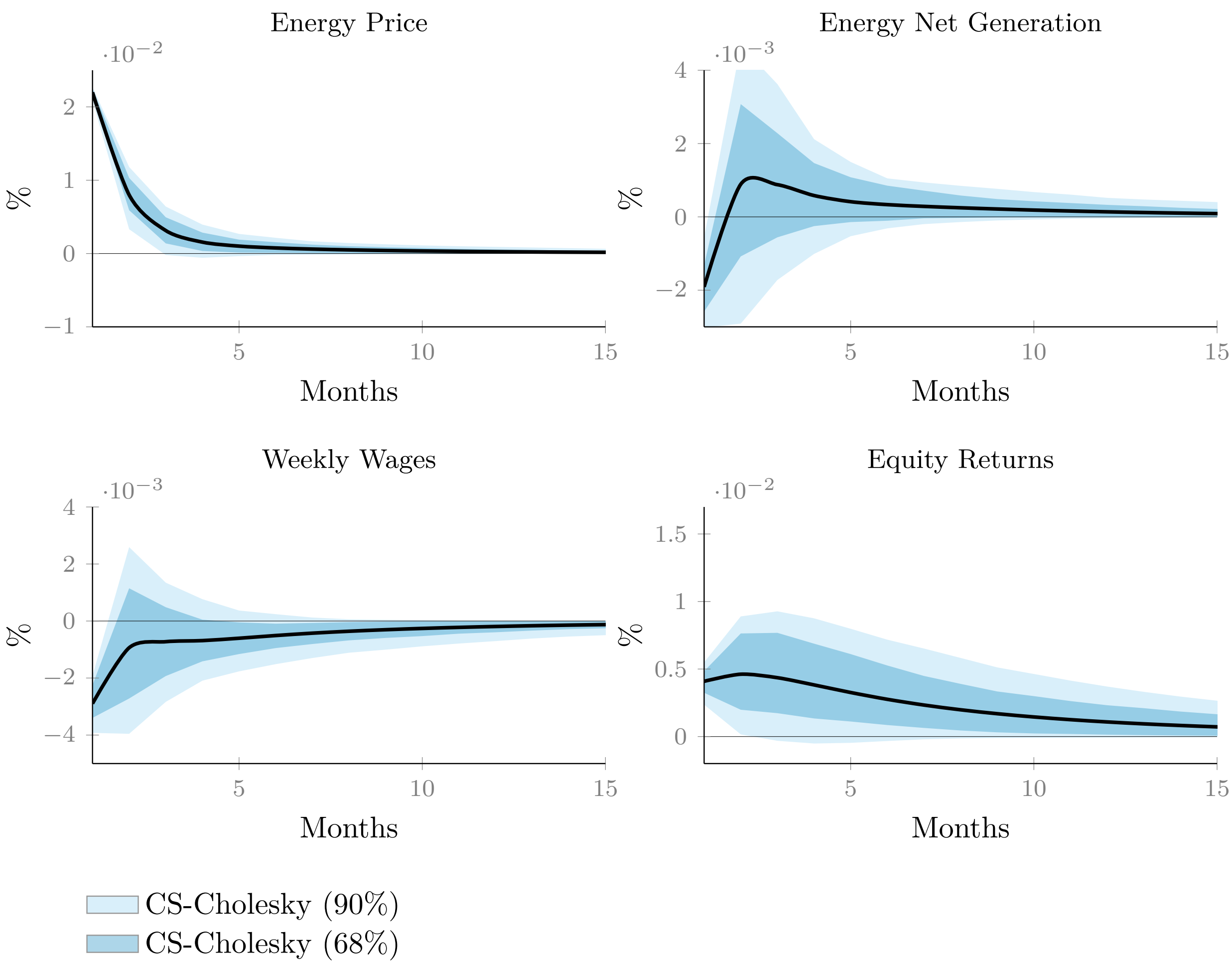
$$Y_t = \begin{pmatrix} \tau_t^C \\ P_t^{en} \\ E_t^{en} \\ W_t \\ R_t \end{pmatrix} = \begin{pmatrix} \text{Carbon Price Shock} \\ \text{Energy Prices} \\ \text{Energy Cons} \\ \text{Wages} \\ \text{Equity Return} \end{pmatrix}$$

$$A = \begin{pmatrix} a_{11} & 0 & 0 & 0 & 0 \\ a_{21} & a_{22} & 0 & 0 & 0 \\ a_{31} & a_{32} & a_{33} & 0 & 0 \\ a_{41} & a_{42} & a_{43} & a_{44} & 0 \\ a_{51} & a_{52} & a_{53} & a_{54} & a_{55} \end{pmatrix}$$

A.4 SVAR Results

Similarly, to the IV-SVAR results presented in the main empirical section of the paper, on impact energy prices increase, which lead to a decrease in energy net-generation, and thereafter a fall in wages and an increase in equity return. The Cholesky IRF results are aligned to the IV-SVAR results.

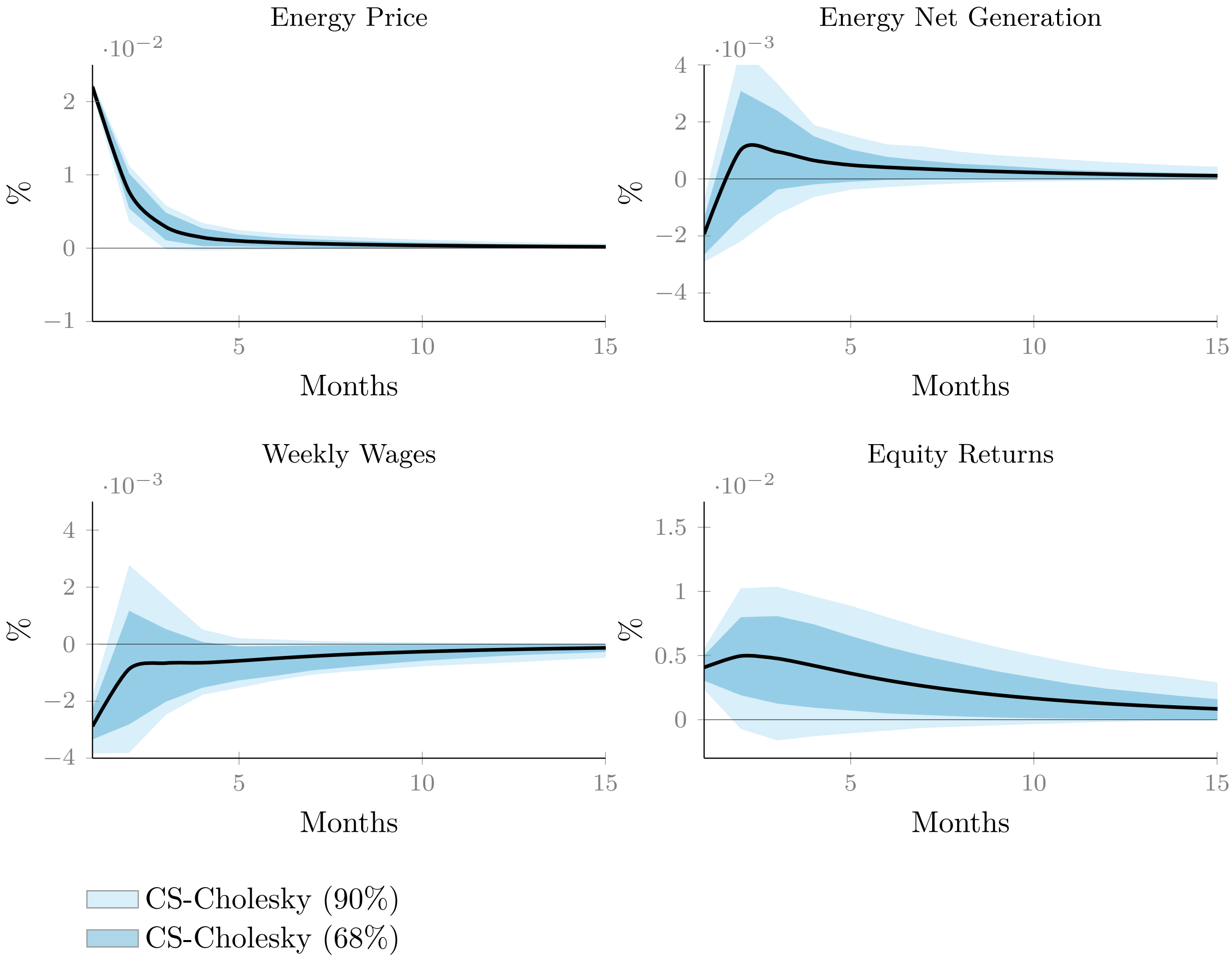
FIGURE XXVII. SVAR with Cholesky Decomposition



Note: The figure presents a 1 lagged SVAR where the carbon policy instrument (with all zero news days are included) is used as an internal instrument. We rely on the Cholesky decomposition to compute the impulse responses at both 90 percent and 68 percent confidence intervals.

Figure XXVIII presents the results of the Cholesky IRFs where we exclude days of zero news. The results remain robust to the main specification (i.e. where days with no news are included in the sample).

FIGURE XXVIII. SVAR with Cholesky Decomposition



Note: The figure presents a 1 lagged SVAR where the carbon policy instrument (with all zero news days are excluded) is used as an internal instrument. We rely on the Cholesky decomposition to compute the impulse responses at both 90percent and 68 percent confidence intervals.

B Appendix: B

B.1 Appendix: Calibration

TABLE III
Calibrated parameter values (annually)

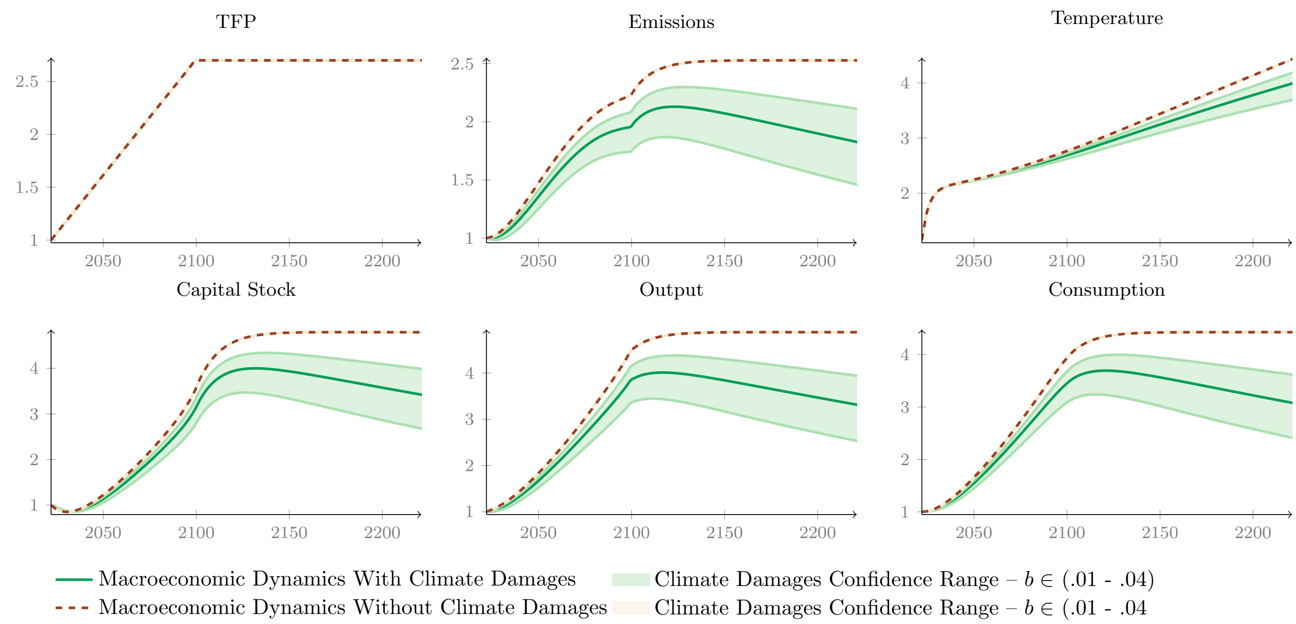
	Calibrated parameters	Values
Standard Macro Parameters		
α^1	Capital intensity for non-energy firms	0.19
α^2	Elasticity of energy to non-energy production	0.15
α^n	Capital intensity for energy firms	2/3
δ	Depreciation rate of capital	0.05
σ	Risk aversion	2
ρ	Discount rate	5%
θ	Price elasticity	6
$\bar{L}$	Labor supply	1/3
Environmental Parameters		
$\bar{e^n}/\bar{e^e} = \varphi^n$	Emissions-to-output ratio in energy sectors	0.3
$\bar{e^y}/\bar{y} = \varphi^y$	Emissions-to-output ratio in non-energy sectors	2
θ_1	Abatement cost parameter	0.1
θ_2	Abatement cost parameter	2.7
θ_3	Abatement learning elasticity	$\in$ (0,1)
ϕ_1^o	Temperature parameter	0.5
ϕ_2^o	Temperature parameter	0.00125
a	Damage function parameter	1.004
b	Damage function parameter	0.02
NK Parameters		
θ^P	Rotemberg quadratic cost parameter	100
ϕ^π	Inflation stance	1.5
ϕ_Y	Output gap reaction parameter	0.1

TABLE IV

Welfare: Net-zero versus Laissez-faire

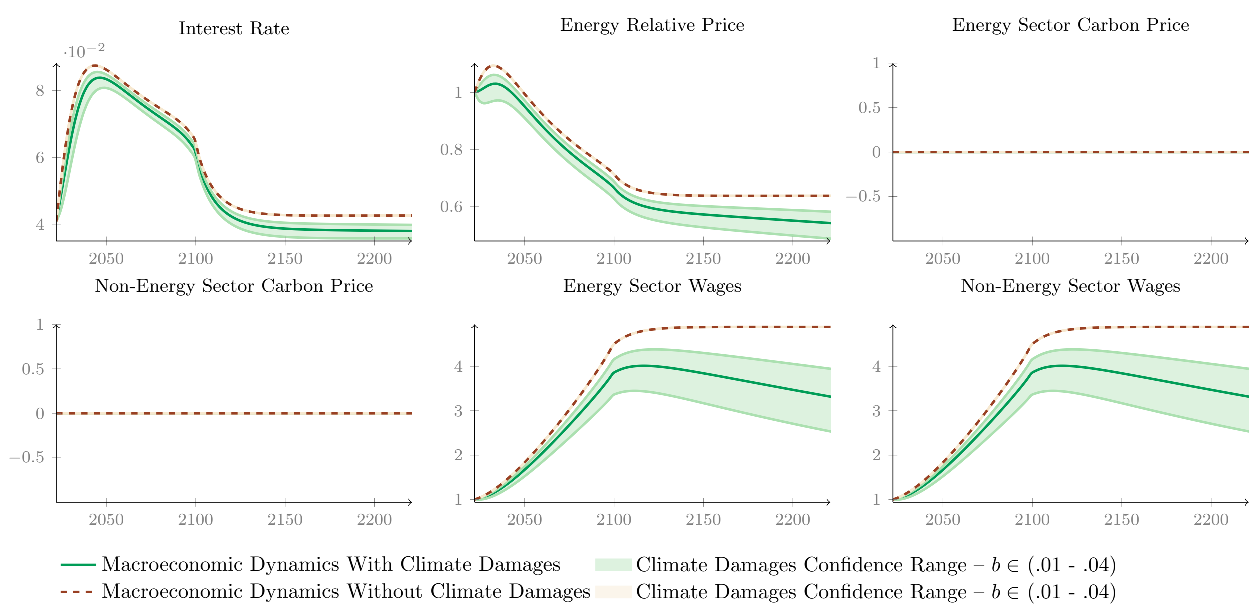
	Welfare Loss
Years	2040 (peak)
ΔWelfare$_t$	24.5%

FIGURE XXIX. Sensitivity To Climate Damages – Macro Aggregates



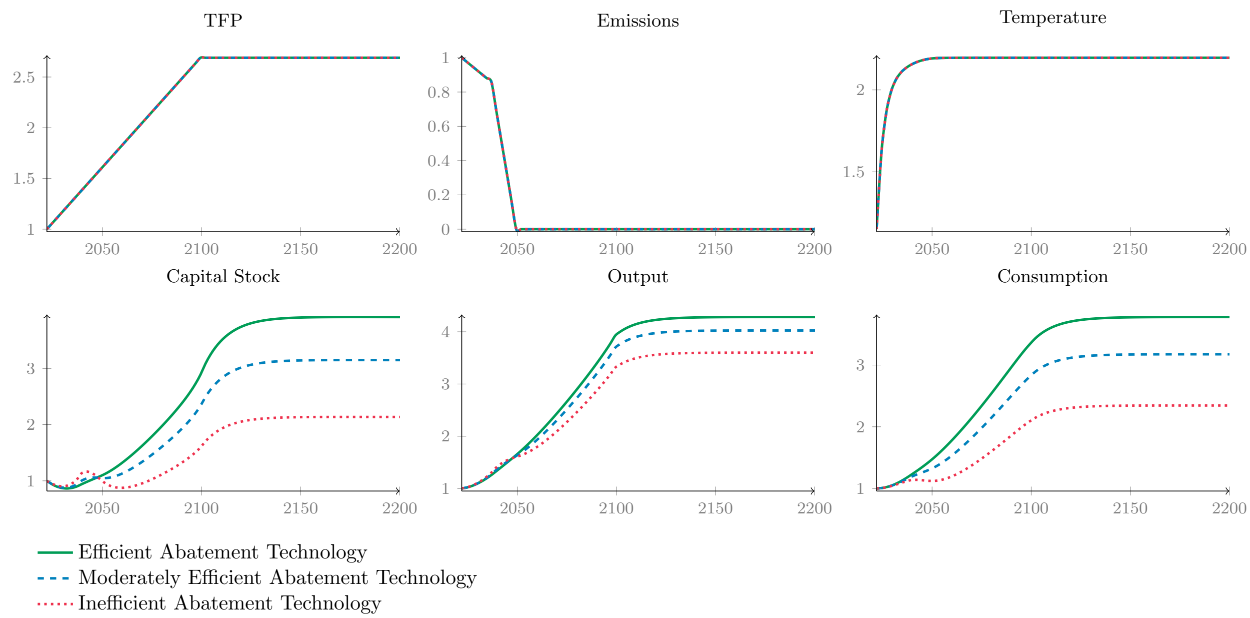
Note: The figure compares transitions computed using a model without climate damages (dashed brown line) to transitions computed using a model with climate damages (solid green line). Brown and green confidence ranges represent confidence range for values of climate damages parameter b as argues by Nordhaus, Dietz, and Weitzman.

FIGURE XXX. Sensitivity To Climate Damages – Prices



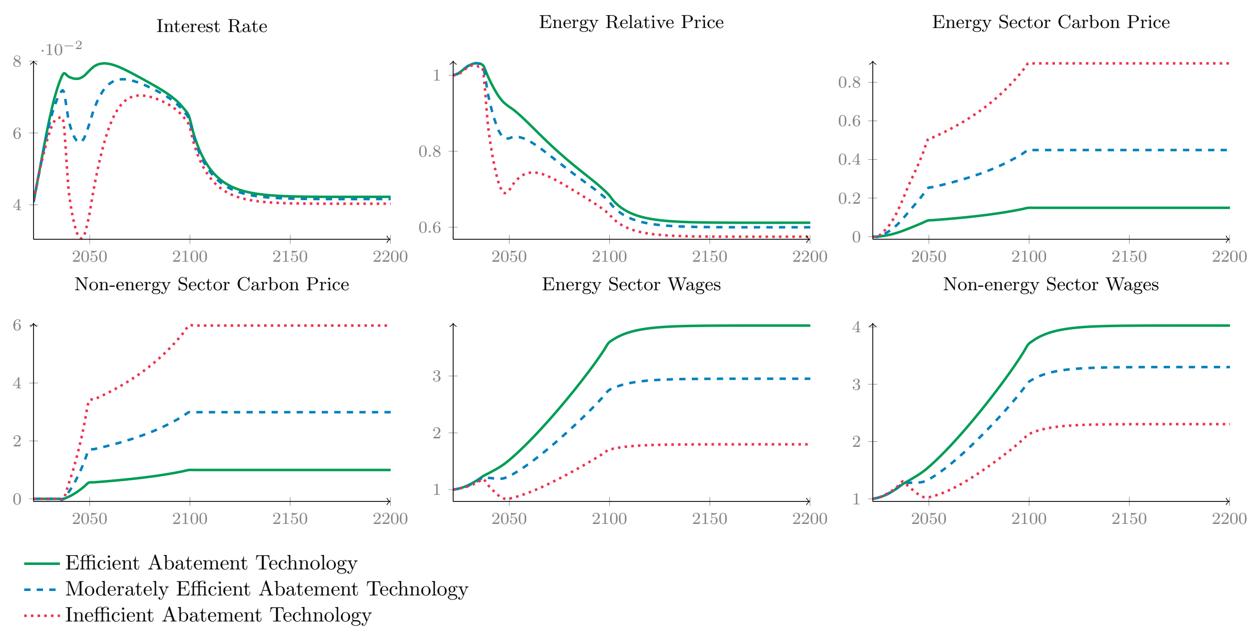
Note: The figure compares transitions computed using a model without climate damages (dashed brown line) to transitions computed using a model with climate damages (solid green line). Brown and green confidence ranges represent confidence range for values of climate damages parameter b as argues by Nordhaus, Dietz, and Weitzman.

FIGURE XXXI. Net-Zero Emission Target and Abatement Efficiency – Macro Aggregates



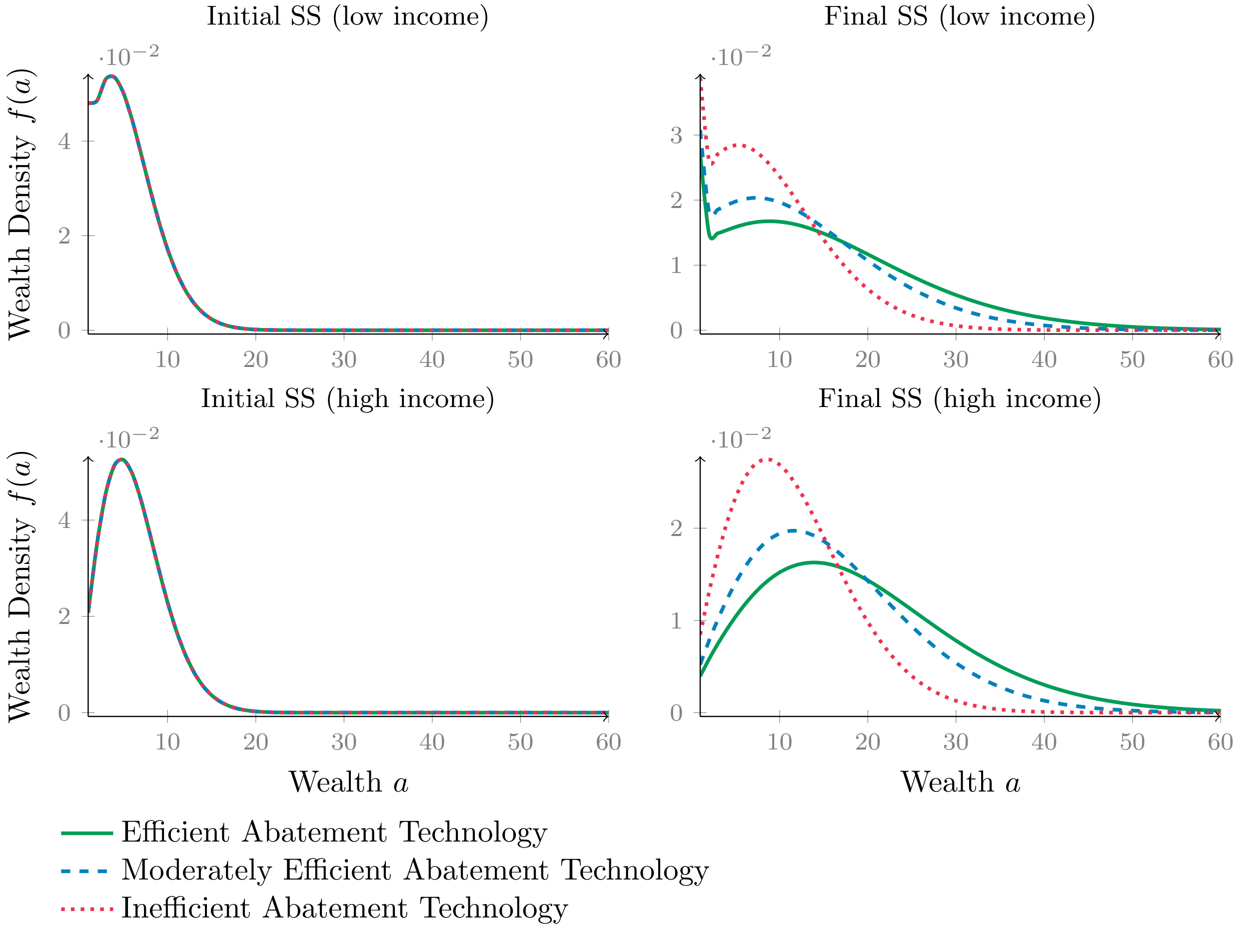
Note: The figure compares transitions under 2 percent growth rate computed using three different abatement cost efficiency levels: i) efficient abatement in green, ii) moderate abatement cost in dashed blue, and iii) inefficient abatement technology with high cost in dotted red.

FIGURE XXXII. Net-Zero Emission Target and Abatement Efficiency – Price



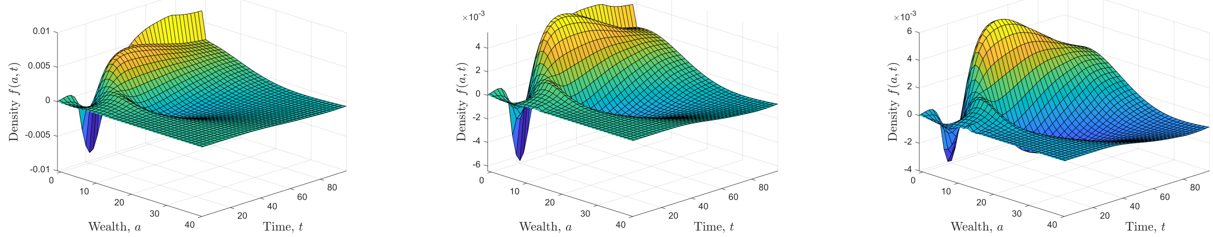
Note: The figure compares transitions under 2 percent growth rate computed using three different abatement cost efficiency levels: i) efficient abatement in green, ii) moderate abatement cost in dashed blue, and iii) inefficient abatement technology with high cost in dotted red.

FIGURE XXXIII. Distributional Impacts of the Net-Zero For Different Abatement Efficiencies



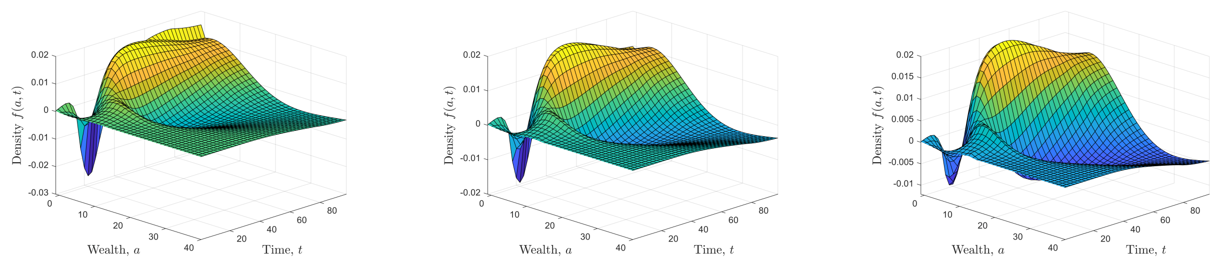
Note: The figure compares initial and final stationary distributions computed using a model with three different abatement cost efficiency levels: i) efficient abatement in green, ii) moderate abatement cost in dashed blue, and iii) inefficient abatement technology with high cost in dotted red.

FIGURE XXXIV. Net-Zero versus Laissez-faire with Efficient Abatement



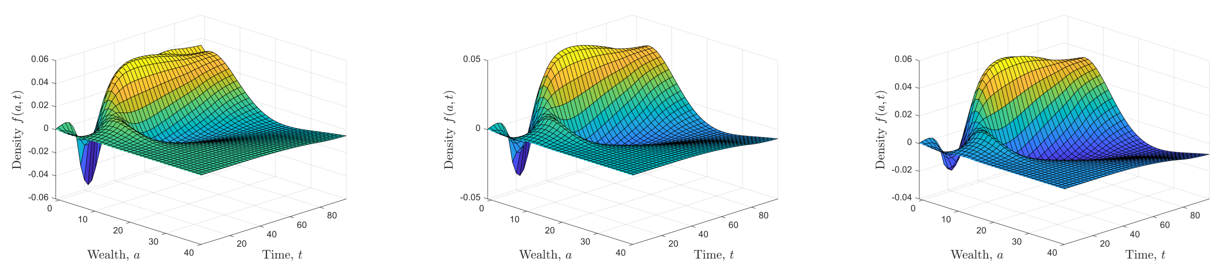
(a) Low Income (b) Average Income (c) High Income

FIGURE XXXV. Net-Zero versus Laissez-faire with Medium Abatement Efficiency



(a) Low Income (b) Average Income (c) High Income

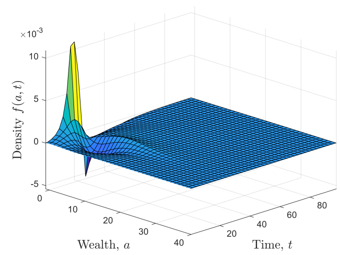
FIGURE XXXVI. Net-Zero versus Laissez-faire with Inefficient Abatement



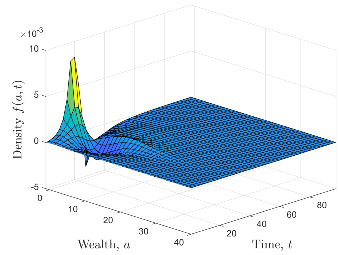
(a) Low Income (b) Average Income (c) High Income

Note: This figure compares the net-zero scenario to a laissez-faire scenario over the transition for the wealth distribution for three different abatement efficiency levels. For example the first row displays the results for efficient abatement costs where figure (a) show the household wealth pathway between 2022 and 2100 for low income households, figure (b) displays the results for average income households, while figure (b) displays the results for high income households. When a point is below zero that means the distribution of wealth across households has improved under the net-zero compared to laissez-faire and vice versa.

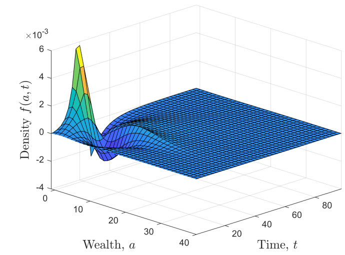
FIGURE XXXVII. Net-Zero with Uniform Fiscal Transfers versus without Transfers – Efficient Abatement



(a) Low Income

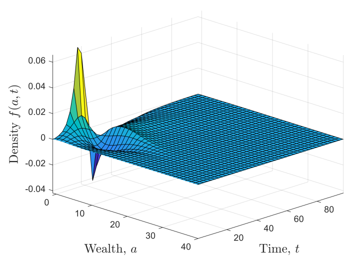


(b) Average Income

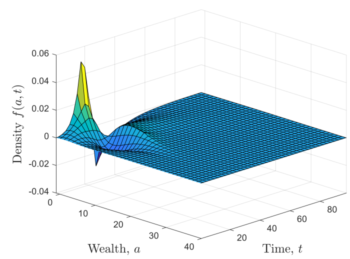


(c) High Income

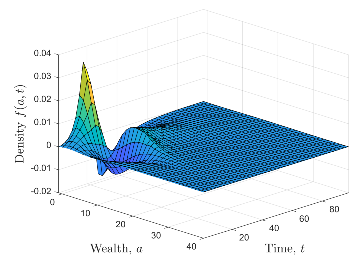
FIGURE XXXVIII. Net-Zero with Uniform Fiscal Transfers versus without Transfers – Inefficient Abatement



(a) Low Income



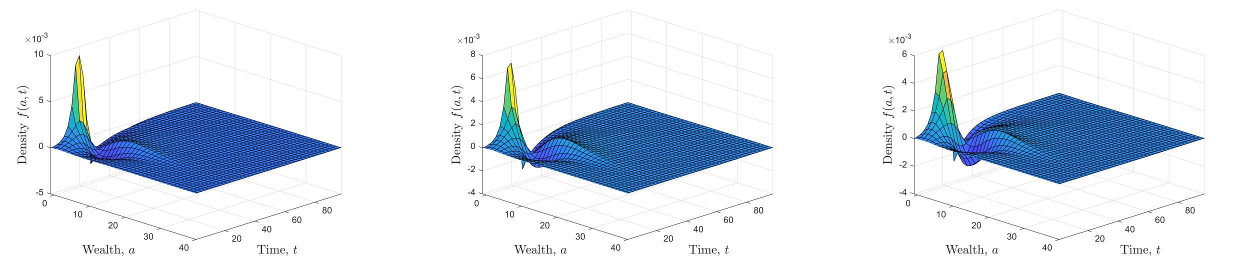
(b) Average Income



(c) High Income

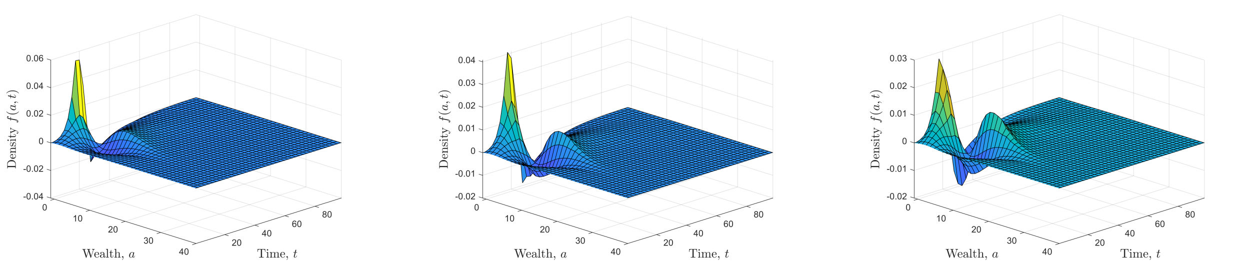
Note: This figure compares the net-zero scenario with uniformly distributed fiscal transfers to the net-zero scenario without fiscal transfers scenario over the transition for the wealth distribution for two different abatement efficiency. For example, in the first row, figure (a) shows the household wealth pathway between 2022 and 2100 for low income households, while figure (b) and figure (c) displays the results for average and high income households, respectively. When a point is below zero that means the distribution of wealth across households has improved under the net-zero with per income distributed fiscal transfers compared to net-zero without fiscal transfers and vice versa.

FIGURE XXXIX. Net-Zero with Fiscal Transfers (by Income) versus without Transfers – Efficient Abatement



(a) Low Income (b) Average Income (c) High Income

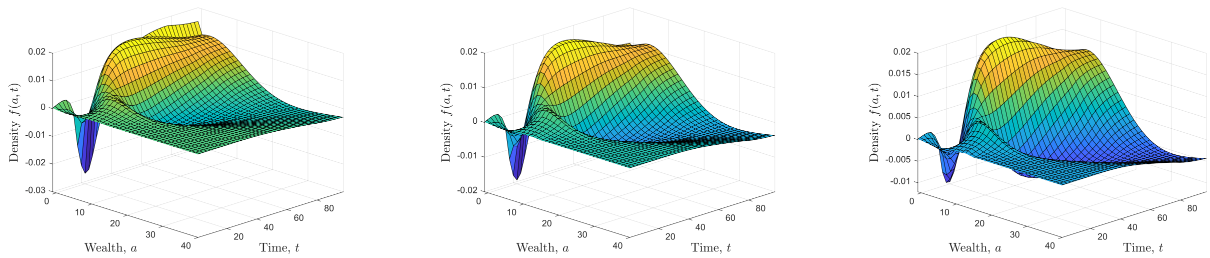
FIGURE XL. Net-Zero with Fiscal Transfers (by Income) versus without Transfers – Inefficient Abatement



(a) Low Income (b) Average Income (c) High Income

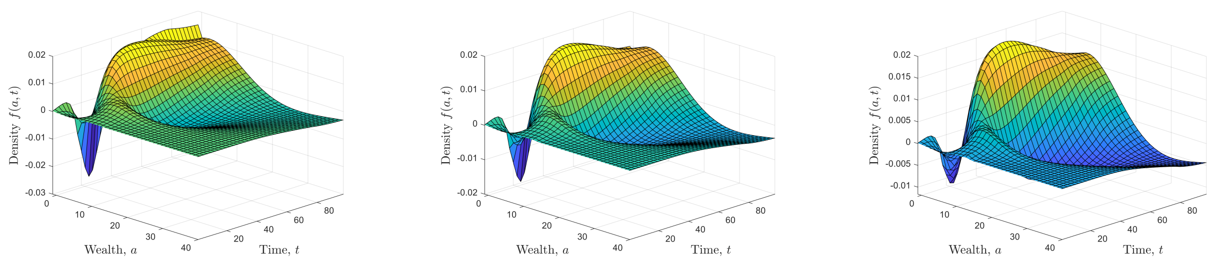
Note: This figure compares the net-zero scenario with per income distributed fiscal transfers to the net-zero scenario without fiscal transfers scenario over the transition for the wealth distribution for two different abatement efficiency. For example, in the first row, figure (a) shows the household wealth pathway between 2022 and 2100 for low income households, while figure (b) and figure (c) displays the results for average and high income households, respectively. When a point is below zero that means the distribution of wealth across households has improved under the net-zero with per income distributed fiscal transfers compared to net-zero without fiscal transfers and vice versa.

FIGURE XLI. Net-Zero versus Laissez-faire with A Linear Trajectory



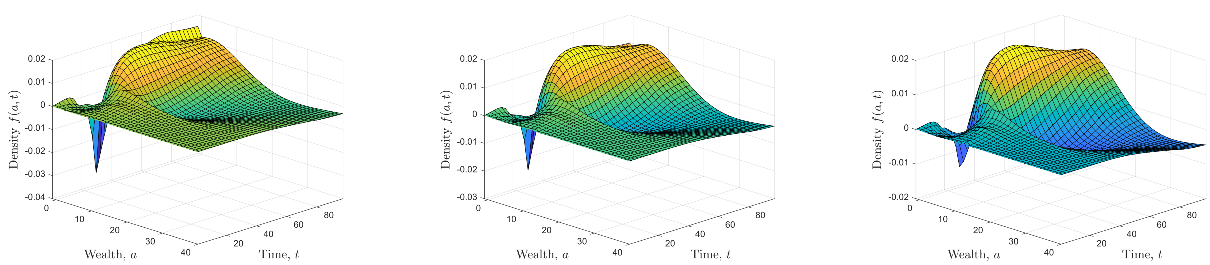
(a) Low Income (b) Average Income (c) High Income

FIGURE XLII. Net-Zero versus Laissez-faire with A Slow Trajectory



(a) Low Income (b) Average Income (c) High Income

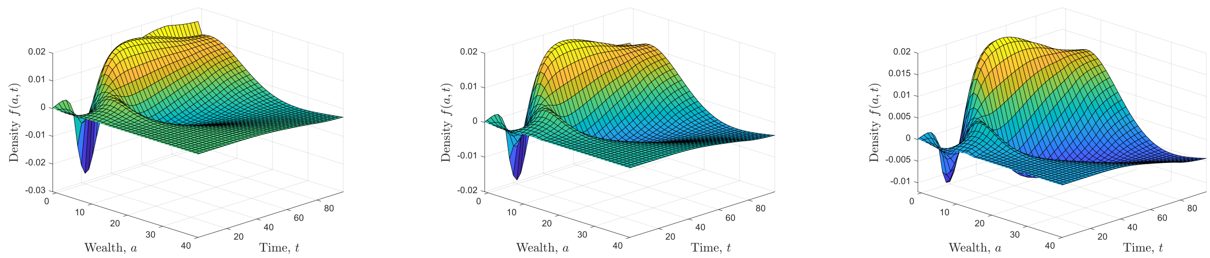
FIGURE XLIII. Net-Zero versus Laissez-faire with A Very Slow Trajectory



(a) Low Income (b) Average Income (c) High Income

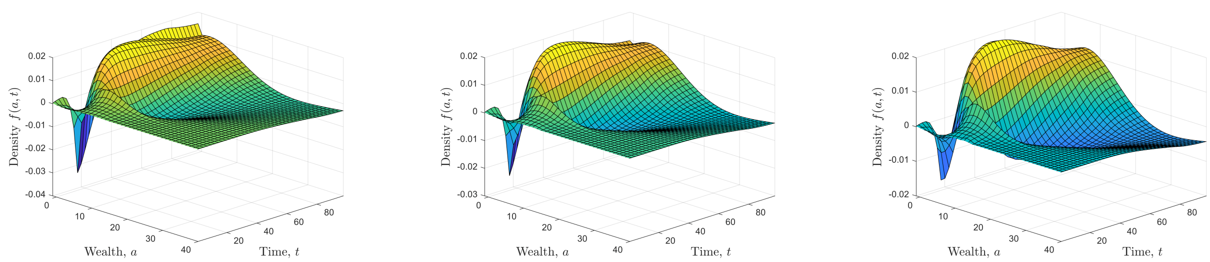
Note: This figure compares the net-zero scenario to a laissez-faire scenario over the transition for the wealth distribution for three different emission cap trajectories (linear, slow, and very slow). For example the first row displays the results for a linear cap trajectory costs where figure (a) show the household wealth pathway between 2022 and 2100 for low income households, figure (b) displays the results for average income households, while figure (b) displays the results for high income households. When a point is below zero that means the distribution of wealth across households has improved under the net-zero compared to laissez-faire and vice versa.

FIGURE XLIV. Net-Zero versus Laissez-faire with A Linear Trajectory



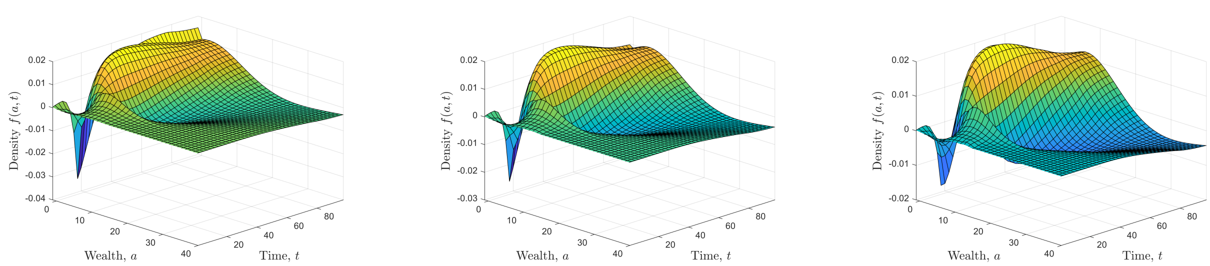
(a) Low Income (b) Average Income (c) High Income

FIGURE XLV. Net-Zero versus Laissez-faire with A Fast Trajectory



(a) Low Income (b) Average Income (c) High Income

FIGURE XLVI. Net-Zero versus Laissez-faire with A Very Fast Trajectory



(a) Low Income (b) Average Income (c) High Income

Note: This figure compares the net-zero scenario to a laissez-faire scenario over the transition for the wealth distribution for three different emission cap trajectories (linear, fast, and very fast). For example the first row displays the results for a linear cap trajectory costs where figure (a) show the household wealth pathway between 2022 and 2100 for low income households, figure (b) displays the results for average income households, while figure (b) displays the results for high income households. When a point is below zero that means the distribution of wealth across households has improved under the net-zero compared to laissez-faire and vice versa.

C Appendix: C

C.1 The Three Box Climate Model

The three box climate dynamics is modeled following Cai and Lontzek [2019] specification. First, the carbon emissions stock M_t law of motion reads:

$$\dot{M}_t = (\Phi_M - I)M_t + b_1 E_t \tag{70}$$

with $M_t = (M_t^{AT}, M_t^{UO}, M_t^{LO})^T$ the three-dimensional vector describing the masses of carbon concentrations in the atmosphere, and upper and lower levels of the ocean. $E_t = \sum_i \int_0^1 e_{i,j,t} dj$ is the total current concentration of carbon dioxide in the atmosphere with $e_{i,j,t}$ the intermediate firm emissions j and sector i and $b_1 = (1, 0, 0)^T$. The matrix Φ_M summarizes the relationship between the actual stocks of emissions and the pre-industrial equilibrium states of the carbon cycle system.

In addition, we define the relationship (as seen in the DICE model) between the temperature vector T_t^o (i.e. both the atmosphere and ocean temperatures) and the stock of emissions in the atmosphere M_t^{AT} as following:

$$\dot{T}_t^o = (\Phi_T - I)T_t^o + b_2 \mathrm{RF}(M_t^{AT}) \tag{71}$$

with $T_t^o = (T_t^{oAT}, T_t^{oOC})^T$ and the matrix Φ_T represents the heat diffusion process between ocean and air. $b_2 = (\xi_T, 0)^T$ with ξ_T the climate sensitivity parameter. Furthermore, atmospheric temperature is affected by radiative forcing, RF(.), which is the interaction between radiation and atmospheric CO_2 as following:

$$\mathrm{RF}(M_t^{AT}) = \eta_F \log_2 \left(\frac{M_t^{AT}}{\bar{M}^{AT}} \right) + \mathrm{RF}_t^{Exo} \tag{72}$$

where RF_t^{Exo} represents the exogenous radiative forcing dynamic and reads as:

$$\mathrm{RF}_t^{Exo} = \begin{cases} -0.06 + 0.0036t, & \text{for t} < 100 \\ 0.3 \text{ otherwise} \end{cases} \tag{73}$$

The impact of global warming on the economy is reflected by the same convex damage function of temperature in the atmosphere presented in the paper:

$$d(T_t^{oAT}) = ae^{-b(T_t^{oAT})^2} \tag{74}$$

C.2 The Non-Energy Firm Problem

The non-energy intermediate firm seeks profit maximization:

$$v(k^y, t) = \max_{p,y,i^y,l^y,\mu^y,e^n} \int_t^\infty e^{-\int_t^s r_u^y du}\, \Pi^F \tag{75}$$

subject to

$$\dot{k}_{j,t}^y = i_{j,t}^y - \delta k_{j,t}^y, \tag{76}$$

$$y_{j,t} = A_t d(T_t^o) k_{j,t}^{y\ \alpha_1} e_{j,t}^{n\ \alpha_2} l_{j,t}^{y\ 1-\alpha_1-\alpha_2}, \tag{77}$$

$$y_{j,t} = \left(\frac{p_{j,t}}{P_t}\right)^{-\theta} Y_t. \tag{78}$$

with profits:

$$\Pi_{j,t}^F = \frac{p_{j,t}}{P_t} y_{j,t} - w_t^y l_{j,t}^y - i_{j,t}^y - p_t^e e_{j,t}^n - f(\mu_{j,t}^y) y_{j,t} - \tau_t^y (1 - \mu_t^y) \varphi_t^y y_{j,t}$$

To solve the problem above, first we solve the cost minimization problem of choosing production inputs to minimize total cost subject to producing at least $y_{j,t}$:

$$\min_{i^y,l^y,\mu^y,e^n} \int_t^\infty e^{-\int_t^s r_u^y du} \text{Cost}^F \tag{79}$$

subject to

$$\dot{k}_{j,t}^y = i_{j,t}^y - \delta k_{j,t}^y, \tag{80}$$

$$A_t d(T_t^o) k_{j,t}^{y\ \alpha_1} e_{j,t}^{n\ \alpha_2} l_{j,t}^{y\ 1-\alpha_1-\alpha_2} \geq y_{j,t}. \tag{81}$$

where,

$$\text{Cost}^F = w_t^y l_{j,t}^y + i_{j,t}^y + p_t^e e_{j,t}^n + f(\mu_{j,t}^y) y_{j,t} + \tau_t^y (1 - \mu_t^y) \varphi_t^y y_{j,t}. \tag{82}$$

The optimality conditions are:

$$\lambda_t^y = 1 \tag{83}$$

$$r_t^y \lambda_t^y - \dot{\lambda}_t^y = \alpha_1 \frac{y_t}{k_t^y} \varrho_t^y - \delta \lambda_t^y, \tag{84}$$

$$p_t^e = \varrho_t^y \alpha_2 \frac{y_t}{e_t^n}, \tag{85}$$

$$w_t = \varrho_t^y (1 - \alpha_1 - \alpha_2) \frac{y_t}{l_t^y}, \tag{86}$$

$$\tau_t^y = \frac{f(\mu_t^y)'}{\varphi_t^y}, \tag{87}$$

where λ_t^y is the co-state, while the ϱ_t^y is the shadow value of input costs. In addition, the transversality condition reads:

$$\lim_{t \to \infty} k_{j,t}^y \lambda_t e^{-\int_0^t r_u^y du} \leqslant 0 \tag{88}$$

Using these first order conditions and the expression of profits ($\Pi^F = \left(\frac{p_{j,t}}{P_t} - mc_t\right) y_{j,t}$) we can then retrieve the expression of the total marginal cost $mc_t = \varrho_t^y + f(\mu_t^y) + \tau_t^y \varphi_t^y (1 - \mu_t^y)$.

Furthermore, using equation (22) as well as equation (16), we can derive the marginal cost and profit of the firms by solving the firms maximization problem:

Case of flexible prices (i.e. Real Business Cycles)

$$v(p_j, t) = \max_{p_j} \int_t^\infty e^{-\int_t^s r_u^y du} \, \Pi^F \tag{89}$$

s.t.

$$y_{j,t} = \left(\frac{p_{j,t}}{P_t}\right)^{-\theta} Y_t. \tag{90}$$

where,

$$\Pi^F = \left(\frac{p_{j,t}}{P_t} - mc_t\right) y_{j,t}. \tag{91}$$

The first order condition yields the price level p_t as firms are all identical (i.e. $p_{j,t} = p_t$) :

$$\frac{p_t}{P_t} = \frac{\theta}{\theta - 1} mc_t \tag{92}$$

Using the symmetric equilibrium condition where $P_t = p_t$, we can rewrite the marginal cost and profits as follows:

$$mc_t = \frac{\theta - 1}{\theta} \tag{93}$$

$$\Pi_t^F = (1 - mc_t)Y_t \tag{94}$$

Case of sticky prices (i.e. New-Keynesian)

$$v(p_j, t) = \max_{p_j} \int_t^{\infty} e^{-\int_t^s r_u^y du} \left(\tilde{\Pi}^F - \Delta^P\right) \tag{95}$$

where,

$$\tilde{\Pi}_{j,t}^F = \left(\frac{p_{j,t}}{P_t} - mc_t\right)\left(\frac{p_{j,t}}{P_t}\right)^{-\theta} Y_t, \tag{96}$$

$$\Delta_{j,t}^P = \frac{\theta^P}{2}\left(\frac{\dot{p}_{j,t}}{p_{j,t}}\right)^2 Y_t. \tag{97}$$

The Hamiltonian of this problem (where we drop j for ease for writing as all firms are subject to same input costs) reads as:

$$H(p, \dot{p}, \lambda^p, t) = \tilde{\Pi}_t^F - \Delta_t^P + \lambda_t^p \dot{p}_t \tag{98}$$

The first order condition yields:

$$\lambda_t^p = \theta^P \frac{\dot{p}_t}{p_t}\frac{P_t}{p_t} Y_t, \tag{99}$$

$$\dot{\lambda}_t^p = r_t^y - \left((1-\theta)\frac{p_t}{P_t}Y_t + \theta\frac{mc_t}{p_t}\left(\frac{p_t}{P_t}\right)^{-\theta} Y_t + \theta^P\left(\frac{\dot{p}_t}{p_t}\right)^2 \frac{P_t}{p_t} Y_t\right). \tag{100}$$

where λ_t^p is the co-state.

Using the symmetric equilibrium condition once again ($P_t = p_t$) and setting inflation $\pi_t = \frac{\dot{p}_t}{p_t}$, we can rewrite the optimality conditions as follows:

$$\lambda_t^p = \theta^P \pi_t Y_t, \tag{101}$$

$$\dot{\lambda_t}^p = r_t^y \lambda_t^p - \left((1-\theta)Y_t + \theta\frac{mc_t}{P_t}Y_t + \theta^P {\pi_t}^2 Y_t\right). \tag{102}$$

Differentiating the first optimality condition with respect to time, we get:

$$\theta\dot{\pi}_t Y_t + \theta\pi_t\dot{Y}_t = \dot{\lambda}^p_t, \tag{103}$$

Finally we substitute this last equation into the equation for co-state and rearrange to get:

$$\left(r^a_t - \frac{\dot{Y}_t}{Y_t}\right)\pi_t = \frac{\theta}{\theta^P}(mc_t - mc^*) + \dot{\pi}_t \tag{104}$$

where, $mc^* = \frac{\theta-1}{\theta}$.

Finally, firms profit after price adjustment costs read as follows:

$$\Pi^F_t = (1 - mc_t)Y_t - \frac{\theta^P}{2}{\pi_t}^2 Y_t. \tag{105}$$

C.3 The Energy Firm Problem

Similar to the non-energy intermediate firms, the energy firms problem reads as:

$$v(k^n, t) = \max_{i^n, k^n, l^n, \mu^n} \int_t^\infty e^{-\int_t^s r^e_u du}\, \Pi^E \tag{106}$$

subject to

$$\dot{k}^n_{j,t} = i^n_{j,t} - \delta k^n_{j,t} \tag{107}$$

and where:

$$\begin{aligned}\Pi^E_{j,t} =& p^e_t A^n_t {k^n_{j,t}}^{\alpha_n} {l^n_{j,t}}^{1-\alpha_n} - w^n_t l^n_{j,t} - i^n_{j,t} \\ & - f(\mu^n_{j,t}) A^n_t {k^n_{j,t}}^{\alpha_n} {l^n_{j,t}}^{1-\alpha_n} - \tau^n_t \varphi^n_t (1-\mu^n_t) A^n_t {k^n_{j,t}}^{\alpha_n} {l^n_{j,t}}^{1-\alpha_n}\end{aligned} \tag{108}$$

The Hamiltonian of this problem reads as:

$$H(., \lambda^n, t) = \Pi^E + \lambda^n_t (i^n_t - \delta k^n_t) \tag{109}$$

The optimality conditions are:

$$\lambda_t^n = 1 \tag{110}$$

$$r_t^e \lambda_t^n - \dot{\lambda}_t^n = \alpha_n \frac{e_t^n}{k_t^n} \left(p_t^e - f(\mu_t^n) - \tau_t^n \varphi_t^n (1-\mu_t^n)\right) - \delta \lambda_t^n, \tag{111}$$

$$w_t^n = (1-\alpha_n) \frac{e_t^n}{l_t^n} \left(p_t^e - f(\mu_t^n) - \tau_t^n \varphi_t^n (1-\mu_t^n)\right), \tag{112}$$

$$\tau_t^n = \frac{f(\mu_{j,t}^n)'}{\varphi_t^n}, \tag{113}$$

and the transversality condition:

$$\lim_{t\to\infty} k_{j,t}^n \lambda_t e^{-\int_0^t r_u^e du} \leqslant 0 \tag{114}$$

We can then note that $\varrho_t^e = p_t^e - f(\mu_t^n) - \tau_t^n \varphi_t^n (1-\mu_t^n)$ is the energy production input cost.

Green Asset Pricing[*]

Ghassane Benmir[1] Ivan Jaccard[2] Gauthier Vermandel[3]

October 26, 2022

Abstract

How do environmental policies affect financial markets? This paper finds that well-designed environmental policies could lead to lower risk premiums and higher real interest rates. We obtain this result by introducing an optimal environmental policy into a business cycle model in which finance matters. By correcting the externality responsible for climate change, the optimal policy reduces the welfare cost of business cycle fluctuations. This decline in aggregate risk in turn lowers the compensation demanded by investors for holding risky assets as well as the need for precautionary savings. Business cycle variations in environmental policies also have substantial welfare implications.

Keywords: Climate Change, Nonseparable Preferences, Stochastic Discount Factor, Natural Rate of Interest.

JEL: Q58, G12, E32.

[*]This draft has benefited from comments and suggestions by M. Andreasen, F. Budianto, J. Cochrane, S. Dietz, S. Giglio, U. Jermann, M. Piazzesi, A. Pommeret, R. Van der Ploeg, P. St-Amour, A. Clark, S. Ben Said, an anonymous referee (ECB Working Paper Series) and seminar and conference participants at the Bank of Finland, the ECB, Aarhus University, Paris-Dauphine University, Paris-Saclay University, ASSA 2021 and the 2021 EFA Meeting.

[1]London School of Economics and Political Science, Houghton Street, London WC2A 2AE, UK. University Paris Dauphine – PSL Research University, LEDa UMR CNRS 8007, Place du Maréchal de Lattre de Tassigny, 75775 Paris Cedex. E-mail: g.benmir@lse.ac.uk.

[2]European Central Bank, 60314 Frankfurt am Main, Germany. The views expressed in this article are those of the authors and do not reflect the views of the ECB. E-mail: ivan.jaccard@ecb.europa.eu.

[3]Ecole Polytechnique, Department of Applied Mathematics CMAP – UMR 7641, Route de Saclay, 91128 Palaiseau Cedex. University Paris Dauphine – PSL Research University, LEDa UMR CNRS 8007, Place du Maréchal de Lattre de Tassigny, 75775 Paris Cedex 16, France. E-mail: gauthier@vermandel.fr

1 Introduction

Following the Paris accords, many governments around the world have committed to reduce their carbon dioxide (CO_2) emissions to address the formidable challenge posed by climate change. Given the scale of the problem, understanding how these policies affect financial markets and welfare is a pressing issue.

This paper studies this question by deriving the optimal carbon tax in the presence of an environmental externality. The novelty of our approach is to investigate the link between asset pricing theory—in particular the stochastic discount factor (SDF)—and climate policies. The SDF is a key building block of modern asset-pricing theory (e.g., Cochrane, 2011). Our main contention is that the SDF also has a critical impact on the design of the optimal carbon tax, and, hence, welfare.

We find that environmental policies can affect asset valuations by correcting the externality responsible for climate change. The intuition for this result is that the externality at the root of climate change is a source of inefficient business cycle volatility. As this volatility increases uncertainty, a well-designed policy can affect aggregate risk in the economy by reducing the welfare cost of business cycle fluctuations (e.g., Lucas, 2003). A reduction in aggregate risk, in turn, affects financial markets by lowering the compensation demanded by investors for holding risky assets. A more stable and a less uncertain macroeconomic environment also decreases the need for precautionary savings, which leads to higher real interest rates.

Why is the environmental externality a source of inefficient volatility? Without policy intervention, the source of the problem is that carbon emissions have no price. Under the optimal policy, in contrast, we show that the price of carbon is time-varying and procyclical. Indeed, without an increase in the price of carbon during booms, the problem is that firms choose a level of production that is inefficient because the return on capital is too high when firms do not consider the effect of capital accumulation, and, hence, production, on carbon emissions. Consequently, there is too much investment during booms, which implies increases in production that are excessive relative to the first-best equilibrium.

The optimal policy corrects this inefficiency by reducing the marginal productivity of capital during booms. An increase in the price of carbon, which is achieved by taxing emissions, forces firms to internalize the effect of production on carbon emissions. The tax lowers the incentive to invest during booms, as firms choose to reduce production to decrease the cost of emitting carbon into the atmosphere.

In addition, introducing a tax on emissions creates an incentive to make the production process cleaner by abating emissions. Under the optimal policy, the tax creates an incentive for firms to shift resources from investment to carbon abatement. As a result, during booms, firms accumulate less capital and devote more resources to emissions-reducing technologies. This climate mitigation margin facilitates consumption smoothing by making the economy more flexible and, hence, more resilient to shocks.

Why is the optimal environmental tax procyclical? Following many approaches in the literature (Stokey, 1998; Acemoglu, Aghion, Bursztyn, and Hemous, 2012; Golosov, Hassler, Krusell, and Tsyvinski, 2014 and Barrage, 2020), we assume that the stock of carbon emissions is a source of disutility for households. We then show that the optimal carbon tax can be expressed as the infinite discounted sum of the marginal disutility caused by the stock of emissions. Relative to the work of Heutel (2012), the first key difference is that we obtain this result in a model in which the environmental externality affects consumers.[1] The second key difference is that the procyclical fluctuations in the optimal tax that we obtain are essentially due to the SDF. A procyclical carbon tax reduces uncertainty by cooling down the economy in booms and by stimulating it in recessions.

To obtain realistic fluctuations in the SDF (e.g., Cochrane and Hansen, 1992), we introduce a specification of slow-moving internal habits. Relative to Constantinides (1990), our specification of habits formalizes the notion that households become accustomed to a particular lifestyle that not only depends on consumption but also on the quality of their environment, which is proxied by the stock of emissions. The effect of the environmental externality is captured by adopting a nonseparable specification of utility that is inspired from the work of Abel (1990). As the stock of emissions harms consumers, utility depends on the ratio between consumption and emissions stocks accumulated into the atmosphere.

As demonstrated by Tallarini (2000), the welfare cost of the business cycle fluctuations is significantly higher in models able to generate risk premiums of a realistic magnitude. In our framework, a key difference is that the link between the optimal tax and the SDF breaks the classic dichotomy between macroeconomics and finance (e.g., Cochrane, 2017

The reason is that the model's ability to reproduce basic asset pricing moments, such as a 3 percent bond premium, has a critical impact on the SDF. Since the SDF is the most important component of the optimal tax, the model's financial market implications matter for the design of environmental policies, and, hence, welfare. In contrast, with

[1] In Heutel (2012) versus the production side of the economy.

a standard preference specification, we find that the dichotomy between climate policies and finance is close to perfect.

Our model's ability to generate a realistic risk premium implies a welfare cost considerably higher than that obtained by Lucas (2003). At the same time, the value that we obtain remains in the lower range of what is typically reported in asset pricing studies (e.g., Barlevy, 2005). In our macro-finance framework, we also find substantial welfare gains from implementing the optimal time-varying carbon tax. Business cycle variations in environmental policies are therefore relevant from a policy perspective. Indeed, the magnitude of the reduction in the welfare cost that we obtain is sizeable, especially when compared to what is generally documented in the macroeconomics literature.

An important contribution of our paper is its estimation of the optimal environmental tax using Bayesian methods. From a computational perspective, the challenge is to estimate this model using a nonlinear solution method as uncertainty; hence, higher-order terms in the Taylor expansion, play a central role in our analysis. A main advantage of our approach is that it allows us to estimate the *laissez-faire* equilibrium using U.S. data and then provide a counterfactual scenario that shows, given the shocks that hit the economy, how the optimal tax would have varied over the business cycle. The outcome of this empirical procedure is shown in Figure 1.

Our paper is related to the asset pricing literature that connects climate change and asset valuation. The growing literature studying interactions between climate change and financial markets is reviewed in Giglio, Kelly, and Stroebel (2020). A review of the macrofinancial implications of climate change is provided by Van Der Ploeg (2020). In this literature, Bansal, Kiku, and Ochoa (2019) find evidence that climate-change risk could already be reflected in current equity prices. In Bansal et al. (2019), this link is explored in a model in which climate change is a source of long-run risk (e.g., Bansal and Yaron, 2004). The long-run risk approach relies on Epstein-Zin-Weil preferences (e.g., Epstein and Zin, 1989; Weil, 1989; Weil, 1990). Eliet-Doillet and Maino (2022) develop an intermediary asset pricing framework that incorporates some key building blocks of integrated assessment models (IAMs) to study unconventional monetary policy.

Our mechanism is closely related to the literature that studies the macroeconomic implications of adaptation measures (e.g., Fried, 2021; Gourio and Fries, 2020). Relative to this literature, our study focuses on measures that reduce the quantity of emissions by introducing an abatement technology. Mitigation measures represent investments in technologies that do not increase the production potential of a firm but reduce emissions. Such measures could include carbon capture technologies or the adoption of renewable sources of energy.

Our approach is also related to a literature that studies the carbon tax within general equilibrium models with production. Golosov et al. (2014) derive the optimal carbon tax in a multisector neoclassical model. These authors show that the optimal tax takes a simple form and critically depends on discounting. Building on the seminal paper of Nordhaus (2008), Barrage (2020) studies carbon taxes in the presence of distortionary fiscal policy. Relative to the case in which lump-sum taxes are used, the optimal tax is lower when the government needs to resort to distortionary taxes. Our findings are also related to Gollier (2021) who highlights the role of abatement technologies and their efficiency in shaping carbon pricing. Heutel (2012) is one of the first papers to consider environmental externalities from a business-cycle perspective (see also Fischer and Springborn (2011)). Although this is a model in which the environmental externality affects the production side of the economy, Heutel (2012) also finds that the optimal carbon tax is procyclical.

In contrast with this latter strand of the literature, our model reproduces a bond premium of approximately 3 percent. Reproducing a bond premium of this magnitude is a challenge for standard macroeconomic models. As in Dew-becker (2014), we obtain this sizeable bond premium in a dynamic stochastic general equilibrium model estimated using Bayesian methods.

Another strand of literature analyzes the role of uncertainty in shaping the carbon taxation. In Van Der Ploeg, Hambel, and Kraft (2020), the optimal carbon tax is derived in an endogenous-growth model with dirty and green capital. The authors show that climate disasters have a significant impact on asset prices and also find that the natural rate of interest is lower under *laissez-faire*. In Van Den Bremer and Van Der Ploeg (2021), the effect of risk attitudes and uncertainty in the social cost of carbon is studied in a model with recursive preferences and capital accumulation. As in Golosov et al. (2014), one advantage of their approach is that they can derive closed-form expressions. Similarly, Cai and Lontzek (2019) show how uncertainty impacts the level of the social cost of carbon. Bauer and Rudebusch (2021) also argue that the decline in the natural interest rate observed over the last decade implies a dramatic increase in the social cost of climate change.

The works of Baker, Bergstresser, Serafeim, and Wurgler (2018) and Zerbib (2019), among others, have shown that pro-environmental preferences affect asset pricing dynamics. They both find a positive and significant premium between green and nongreen bonds (i.e., the 'greenium'), suggesting an important role for these preferences in relation to the ongoing debate on carbon taxation. In Pàstor, Stambaugh, and Taylor (2021), the effect of climate change on financial returns is explained by introducing a green factor that captures environmental concerns on the part of investors.

Regarding the role of nonseparability in asset pricing, our study is also related to the work of Piazzesi, Schneider, and Tuzel (2007). As these authors have shown, nonseparability between consumption and other components of the utility function can affect marginal utility and, hence, asset prices.

Finally, another major concern for policy-makers is that the predicted effect of climate policies on the economy is strongly model dependent. This issue is studied in Barnett, Brock, and Hansen (2021), who show how the risk of model misspecification can affect the formulation of climate policies. Barnett, Brock, Hansen, and Hong (2020) study a framework with risk as well as uncertainty about the choice and specification of models, and discuss how these different sources of uncertainty affect stochastic discounting.

2 The model

Consider a business-cycle model characterized by discrete time and an infinite-horizon economy populated by *firms* and *households*, which are infinitely lived and of measure one. In this setup, production by firms creates an environmental externality via emissions, and these latter affect household welfare by reducing the utility stemming from the consumption of goods. Firms do not internalize the social cost from emissions of CO_2. As such, there is market failure, opening the door to optimal policy intervention.

As the contribution of the paper lies in the role of the environmental externality in shaping investors' risk behavior, we start by presenting the balanced growth path, we next explain the accumulation of emissions in the atmosphere. We then explain how this environmental externality affects households' behavior.

2.1 Balanced growth

Given that one objective of this paper is to estimate the model, we need to consider that emissions grow at a different rate from output. In the context of our model, this difference in growth rates can be explained by introducing a rate of green technological progress.

As is standard in the literature, macroeconomic variables are also assumed to grow along the balanced growth path. This is achieved by introducing labor-augmenting technological progress, denoted by Γ_t. The growth rate of labor-augmenting technological progress is γ^Y, where:

$$\frac{\Gamma_{t+1}}{\Gamma_t} = \gamma^Y. \tag{1}$$

We denote Green technological progress in the growing economy by Ψ_t. The growth rate of Green progress γ^E is as follows:

$$\frac{\Psi_{t+1}}{\Psi_t} = \gamma^E.$$

This trend is necessary to capture the long-term process of decoupling of output growth from emissions growth. As documented by Newell, Jaffe, and Stavins (1999), this trend can be interpreted as an energy-saving technological change that captures the adoption of less energy-intensive technologies in capital goods. An improvement in technology, therefore, implies a value for γ^E that is below 1. As in Nordhaus (1991), we assume that this trend is deterministic.

As in Heutel (2012), emissions grow proportionally to output with elasticity $1 - \varphi_2$ but diverge through exogenous efficiency in carbon intensity. The growth rate of carbon and CO_2 emissions, denoted γ^X, is given by:

$$\gamma^X = \gamma^E \left(\gamma^Y\right)^{1-\varphi_2}. \tag{2}$$

In the following sections, we present the detrended economy. The detailed derivation of this detrended economy appears in Appendix C.

2.2 Firms and emissions

A large subsequent class of models derived from IAMs (such as DICE models by Nordhaus) rely on the 'carbon cycle model' framework (e.g., Dietz, van der Ploeg, Rezai, and Venmans 2021), which typically includes multiple reservoirs of carbon. Following recent work of Dietz and Venmans (2019), we adopt a reduced form of the carbon cycle that only features one reservoir of carbon, as this specification enables to match climate dynamics at a business cycle frequency.[2] The accumulation of carbon dioxide and other greenhouse gases (GHGs) in the atmosphere results from the human activity of economic production

[2] We however assess the robustness of our results with three reservoirs of carbon in Appendix E of the paper. In that section, we consider alternative specifications for the climate block. We find that asset pricing effects are robust to different modeling structures of the climate block.

as follows:

$$\gamma^X x_{t+1} = \eta x_t + e_t + e^*, \tag{3}$$

where x_{t+1} is the concentration of gases in the atmosphere, $e_t \geq 0$ the inflow of greenhouse gases at time t, e^* the inflow of rest of the world emissions, and $0 < \eta < 1$ the linear rate of continuation of CO_2-equivalent emissions on a quarterly basis. To allow a convergence in the law of motion of the stock of emissions process, we slightly depart from the transient climate response to cumulative carbon emissions theory by setting a value of η slightly below unity to mimic the random-walk nature of climate variables.

Anthropogenic emissions of CO_2 result from both economic production and exogenous technical change:

$$e_t = (1 - \mu_t)\, \varphi_1 y_t^{1-\varphi_2} \varepsilon_t^X. \tag{4}$$

Here, the variable $1 \geq \mu_t \geq 0$ is the fraction of emissions abated by firms, y_t is the aggregate production of goods by firms, and variable ε_t^X is an AR(1) exogenous shock. This shock captures cyclical exogenous changes in the energy efficiency of firms.

This functional form for emissions allows us to consider both low- and high-frequency variations in CO_2 emissions. For the high-frequency features of the emissions data, the term $\varphi_1 y_t^{1-\varphi_2}$ denotes the total inflow of pollution resulting from production prior to abatement. In this expression, φ_1 and $\varphi_2 \geq 0$ are two carbon-intensity parameters that, respectively pin down the steady-state ratio of emissions to output and the elasticity of emissions with respect to output over the last century. While φ_2 is set to 0 in Nordhaus (1991), we follow Heutel (2012) and allow this parameter to be positive to capture potential nonlinearities between output and emissions. For $\varphi_2 < 1$, the emissions function exhibits decreasing returns.

The remaining set of equations for firms is fairly standard and similar to Jermann (1998). In particular, the representative firm seeks to maximize profit by making a trade-off between the desired levels of capital and labor. Output is produced via a Cobb-Douglas production function:

$$y_t = \varepsilon_t^A A k_t^\alpha n_t^{1-\alpha}, \tag{5}$$

where k_t is the capital stock with an intensity parameter $\alpha \in [0, 1]$, n_t is labor, $A > 0$ is the productivity level, and ε_t^A is a total factor productivity shock that evolves as follows: $\log\left(\varepsilon_t^A\right) = \rho_A \log\left(\varepsilon_{t-1}^A\right) + \eta_t^A$, with $\eta_t^A \sim N(0, \sigma_A^2)$. The capital-share parameter is denoted by α. Firms maximize profits:

$$d_t = y_t - w_t n_t - i_t - f(\mu_t)\, y_t - e_t \tau_t. \tag{6}$$

The real wage is denoted by w_t, $f(\mu_t)$ is the abatement-cost function, and $\tau_t \geq 0$ a potential tax on GHG emissions introduced by the fiscal authority. Investment is denoted by i_t and the accumulation of physical capital is given by the following law of motion:

$$\gamma^Y k_{t+1} = (1-\delta)k_t + \left(\frac{\chi_1}{1-\epsilon} \left(\varepsilon_t^I \frac{i_t}{k_t} \right)^{1-\epsilon} + \chi_2 \right) k_t, \tag{7}$$

where $\delta \in [0,1]$ is the depreciation rate of physical capital and ε_t^I is an exogenous shock process, as in Christiano, Motto, and Rostagno (2014). This can be interpreted as an investment shock that captures financial frictions associated with asymmetric information or costly monitoring. As in Jermann (1998), χ_1 and χ_2 are two scale parameters that are calibrated to ensure that adjustment costs do not affect the deterministic steady state of the economy. The elasticity parameter $\epsilon > 0$ measures the intensity of adjustment costs.

The abatement-cost function is taken from Nordhaus (2008), where $f(\mu_t) = \theta_1 \mu_t^{\theta_2}$. In this expression, $\theta_1 \geq 0$ pins down the steady state of the abatement, while $\theta_2 > 0$ is the elasticity of the abatement cost to the fraction of abated GHGs. This function $f(\mu_t)$ relates the fraction of emissions abated to the fraction of output spent on abatement, where the price of abatement is normalized to one.

2.3 Households and the environmental externality

We model the representative household via a utility function where the household chooses consumption expenditures as well as its holdings of long-term government bonds. Following Stokey (1998), Acemoglu et al. (2012), Golosov et al. (2014), and Barrage (2020), among others, we introduce the environmental externality into the utility function. To maximize the model's ability to generate realistic asset pricing implications, we study the environmental externality in a model with internal habit formation. The utility of the representative agent is negatively affected by the stock of emissions x and is given as follows:

$$E_0 \sum_{t=0}^{\infty} \beta^t \log \left(\varepsilon_t^B \frac{c_t}{x_t} - h_t \right), \tag{8}$$

where E_0 is the expectations operator conditioned on information at time 0, β the time discount factor, h_t the habit stock, and ε_t^B is an AR(1) preference shock, with $\log \varepsilon_t^B = \rho_B \log \varepsilon_{t-1}^B + \eta_t^B$, $\eta_t^B \sim N(0, \sigma_B^2)$.[3] The law of motion for the habit stock, h_t, depends on

[3] As will be discussed in the next sections, the preference shock has a negligible impact on the mean risk-free rate and risk premium.

the composite good c_t/x_t and is given as follows:[4]

$$\gamma^Y h_{t+1} = m h_t + (1-m)\varepsilon_t^B \frac{c_t}{x_t}. \tag{9}$$

As we discuss in Appendix C, since c_t and x_t are growing at different rates in the steady state, we need an additional assumption in the utility function to obtain a balanced growth path.[5]

Following Fuhrer (2000) and Campbell and Cochrane (1999), among others, a slow-moving component is introduced by assuming that the habit stock does not depreciate completely within the period. The memory parameter, m, where $0 \leq m \leq 1$ captures the rate at which the habit stock depreciates, whereas $1-m$ measures the sensitivity of the reference level with respect to changes in the composite. This specification reduces to the case without habits when m is set to 1.

The budget constraint of the representative household is as follows:

$$w_t n_t + b_t + d_t = c_t + p_t^B (b_{t+1} - b_t) + t_t \tag{10}$$

where the left-hand side refers to the household's different sources of income. Total income is first comprised of labor income (with inelastic labor supply n_t). Every period, the agent also receives income from holding a long-term government bond, b_t. As the representative agent owns firms in the corporate sector, there is also a dividend income of d_t.

On the expenditure side, the representative household first spends its income on consumption goods, c_t. The price at which newly issued government bonds are purchased is p_t^B, and the quantity of new government bonds purchased during the period is $b_{t+1} - b_t$. Finally, we assume that the government levies a lump-sum tax of t_t.

[4] See Jaccard (2014) for a discussion of asset pricing implications of habits in the composite good.

[5] In the growing economy, the disutility caused by the stock of emissions is given by $\Theta_t X_t$, where Θ_t is a trend variable that captures agents' awareness of climate change, and X_t is the stock of emissions. The deterministic variable Θ_t then ensures that the ratio $\frac{C_t}{\Theta_t X_t}$ grows at the rate of labor augmenting technological progress γ^Y. Introducing deterministic trends into the utility function to ensure the existence of a balanced growth path is also a common practice in the literature that uses Epstein-Zin-Weil preferences.

2.4 Government and market clearing

The government finances its expenditures by issuing a bond and collecting taxes. The government budget constraint is as follows:

$$g_t + b_t = p_t^B (b_{t+1} - b_t) + t_t + \tau_t e_t, \tag{11}$$

where public expenditure is denoted by g_t and t_t is a lump-sum tax. The revenue is composed of newly issued government bonds $b_{t+1} - b_t$ on financial markets to households, while $\tau_t e_t$ denotes the revenues obtained from the implementation of an environmental tax on emissions. In this expression, e_t and τ_t are the level of emissions and the tax, respectively. As in any typical business-cycle model, government spending is exogenously determined and follows an AR(1) process: $g_t = \bar{g}\varepsilon_t^G$, with $\log \varepsilon_t^G = \rho_G \log \varepsilon_{t-1}^G + \eta_t^G$, $\eta_t^G \sim N(0, \sigma_G^2)$, and $\bar{g}$ denoting the steady-state amount of resources that is consumed by the government. This shock accounts for changes in aggregate demand driven by changes in both public spending and the trade balance.

The resource constraint of the economy reads as follows:

$$y_t = c_t + i_t + g_t + f(\mu_t)\, y_t. \tag{12}$$

2.5 Marginal utility, the risk premium, and the risk-free rate

For the asset pricing variables, we calculate the risk-free rate and the conditional risk premium[6], respectively as:

$$1 + r_t^F = \left\{\beta^Y E_t \lambda_{t+1}/\lambda_t\right\}^{-1}, \tag{13}$$
$$E_t(r_{t+1}^B - r_t^F) = E_t((1 + p_{t+1}^B)/p_t^B - (1 + r_t^F)), \tag{14}$$

where $\beta^Y \{\lambda_{t+1}/\lambda_t\}$ is the stochastic discount factor, λ_t is the marginal utility of consumption. With our specification of internal habit formation, the marginal utility of consumption is given as follows:

$$\lambda_t = \left(\varepsilon_t^B \frac{c_t}{x_t} - h_t\right)^{-1} \varepsilon_t^B \frac{1}{x_t} - \xi_t (1 - m) \varepsilon_t^B \frac{1}{x_t}, \tag{15}$$

[6] Although the estimated version of the model focuses on the bond premium, the equity premium will be discussed in section 6 below.

where ξ_t is the Lagrange multiplier associated with the law of accumulation of the habit stock in Equation 9. The dynamics of the Lagrange multiplier is determined by the following Euler condition:

$$\xi_t = m\beta^Y E_t \xi_{t+1} + \beta^Y E_t \left(\varepsilon^B_{t+1} \frac{c_{t+1}}{x_{t+1}} - h_{t+1} \right)^{-1}, \tag{16}$$

The modified subjective discount factor β^Y is as follows:

$$\beta^Y = \beta / \gamma^Y \tag{17}$$

3 Welfare theorems with environmental preferences

In this section, we derive the optimal tax by comparing the decentralized equilibrium to the planner's problem.

3.1 The centralized economy

We start by characterizing the first-best allocation and consider the optimal plan that the benevolent social planner would choose to maximize welfare. This equilibrium provides the benchmark against which the allocation obtained in the decentralized economy should be compared.

Definition 1 *The optimal policy problem for the social planner is to maximize total welfare in equation (8) by choosing a sequence of allocations for the quantities* $\{c_t, i_t, y_t, \mu_t, e_t, k_{t+1}, x_{t+1}, h_{t+1}\}$, *for given initial conditions for the two endogenous state variables* k_0 *and* x_0 *that satisfy equations (3), (4), (5), (7), (9), and (12).*

Define q_t as the shadow value of capital and ϱ_t as the Lagrangian multiplier on the production function (note that both q_t and ϱ_t are expressed in terms of the marginal utility of consumption). The first-order conditions with respect to investment and the capital stock for this problem are as follows:

$$1 = \chi_1 \varepsilon^I_t q_t \left(\varepsilon^I_t \frac{i_{t+1}}{k_{t+1}} \right)^{-\epsilon},$$

$$q_t = \beta^Y E_t \frac{\lambda_{t+1}}{\lambda_t} q_{t+1} \left[(1-\delta_K) + \frac{\chi_1}{1-\epsilon} \left(\varepsilon_{It+1} \frac{i_{t+1}}{k_{t+1}} \right)^{1-\epsilon} + \chi_2 - \chi_1 \left(\varepsilon_{It+1} \frac{i_{t+1}}{k_{t+1}} \right)^{1-\epsilon} \right] \tag{18}$$
$$+ \beta^Y E_t \frac{\lambda_{t+1}}{\lambda_t} \alpha \frac{y_{t+1}}{k_{t+1}} \varrho_{t+1}$$

where $\beta^Y = \beta/\gamma^Y$.

Letting v_{Et} denote the Lagrange multiplier (expressed in units of marginal utility of consumption) on equation (4), the first-order conditions with respect to the firm's optimal choice of output and abatement are given as follows:

$$\varrho_t + f(\mu_t) + v_{Et}(1-\varphi_2) e_t / y_t = 1, \tag{19}$$
$$v_{Et} e_t / (1-\mu_t) = f'(\mu_t) y_t. \tag{20}$$

The Lagrange multiplier ϱ_t is usually interpreted as the marginal cost of producing a new good, while v_{Et} is the social planner's value of abatement. Equation (19) thus highlights the key role of emissions in shaping price dynamics: the production of one additional unit of goods increases firm profits but is partially compensated by the marginal cost from abating emissions. The planner also takes into account the marginal cost from emitting GHGs in the atmosphere. Note that if the abatement effort is zero, the marginal cost of production is one, as in the standard real business-cycle model. Equation (20) is a standard cost-minimizing condition on abatement: abating CO_2 emissions is optimal when the resulting marginal gain (the left-hand side of equation (20)) is equal to its marginal cost (the right-hand side of the same equation).

Two remaining first-order conditions on each of the environmental variables, then, x_t and e_t are necessary to characterize the decision rules of the social planner:

$$v_{Xt} = \beta^X E_t \frac{\lambda_{t+1}}{\lambda_t} \left(\frac{c_{t+1}}{x_{t+1}} + \eta v_{Xt+1} \right) \tag{21}$$
$$v_{Et} = v_{Xt}. \tag{22}$$

where $\beta^X = \beta/\gamma^X$. Recall that v_{Et} is the Lagrange multiplier on emissions in equation (4), while v_{Xt} is the Lagrange multiplier on the law of motion of GHGs in equation (3).

Equation (21) is the most important equation of the paper. The variable v_{Xt} can be interpreted as the implicit price of carbon. Equation (21) shows that this implicit price can be considered via an asset-pricing formula. The first term $(\beta^X E_t \frac{\lambda_{t+1}}{\lambda_t} \frac{c_{t+1}}{x_{t+1}})$ is the discounted utility loss incurred by society from a marginal increase in the stock of emissions in the atmosphere. The second term ($\eta\{E_t \frac{\lambda_{t+1}}{\lambda_t} v_{Xt+1}\}$) is the continuation value of the discounted utility loss caused by emissions, which remain in the atmosphere with probability η. As in a cost-benefit analysis, v_{Xt} is interpreted as the social cost of carbon (SSC), the cost in current consumption equivalents of a marginal increase in carbon emissions. The second equation is the internal cost of GHG emissions for firms, where v_{Et} is the marginal cost for a firm emitting one kiloton of carbon. In the first-best allocation, this cost must be exactly equal to the price of carbon emissions v_{Xt}.

It should also be emphasized that this asset-pricing formula does not depend on habit formation or the preference shock. It is fairly general and will be obtained in a large class of models in which preferences are homogeneous.

Definition 2 *The inefficiency wedge induced by the environmental externality is defined as the gap between the price of carbon emissions and this marginal cost:* $\varpi_t = v_{Xt} - v_{Et}$.

When the social cost of carbon is perfectly internalized by society, optimal abatement in equation (22) is such that the marginal cost of emissions equals their price. In this case, it is optimal for firms, and society to spend a fraction of resources to reduce CO_2 emissions by using the abatement technology $f(\mu_t)$.

Proposition 1 *In a centralized equilibrium, the social cost of carbon is perfectly internalized by the planner. The marginal cost of emissions is, therefore, equal to the price of carbon emissions. This implies (from the previous definition) a first-best allocation with an inefficiency wedge* $\varpi_t = 0$.

The resulting equilibrium is optimal, as the social cost of the externality is perfectly internalized by society. Consequently, the inefficiency wedge from carbon emissions is zero. In the following section, we show that this optimum is not reached in a *laissez-faire* equilibrium with profit-maximizing firms.

3.2 The competitive equilibrium

We now describe the competitive equilibrium resulting from economic decisions taken by households and firms separately, with no centralization. This decentralized economy is also referred to as the competitive or *laissez-faire* equilibrium, where social preferences for carbon are different across firms and households. We propose the following definition to characterize this economy.

Definition 3 *The laissez-faire equilibrium is defined as a competitive equilibrium in which the environmental tax on carbon emissions τ_t is set to 0. Households maximize utility in Equation 8 under constraints (7) and (10). Firms maximize profits (6) under constraints (4) and (5).*

Relative to the efficient equilibrium, the difference here is that firms maximize profits and no longer consider the stock of CO_2 emissions as a control variable. This implies that firms and households exhibit different preferences regarding carbon emissions. As a result, the price of carbon for firms differs from that obtained in the centralized economy. Since emissions are costly to abate, and given that firms do not internalize the effect of their emissions on consumers, the cost of carbon emissions for firms is zero. In contrast, the price of carbon for households, which we denote v_{Xt}, is given as follows:

$$v_{Xt} = \beta^X E_t \frac{\lambda_{t+1}}{\lambda_t} \left(\frac{c_{t+1}}{x_{t+1}} + \eta v_{Xt+1} \right) \tag{23}$$

Here, we have a market failure, as the social value of carbon differs between the emitters of carbon and the agents who experience social loss.

As emissions are not taxed, the shadow cost for a firm to emit CO_2 in the atmosphere is zero:[7]

$$v_{Et} = 0. \tag{24}$$

In this setup, firms simply cost minimize by optimally choosing zero abatement spending: with a cost of releasing CO_2 of zero, firms have no incentive to allocate resources to use the abatement technology $f(\mu_t)$ to reduce emissions. The socially optimal level of abatement is not implemented, as the equilibrium abatement share is zero in the *laissez-faire* equilibrium:

$$\mu_t = 0. \tag{25}$$

Consequently, the marginal cost of production ϱ_t is similar to that obtained in any typical real business-cycle model. In terms of the notation introduced in definition 3, this produces an environmental inefficiency wedge that differs from zero:

$$\varpi_t = v_{Xt} - v_{Et} = v_{Xt}. \tag{26}$$

CO_2 emissions therefore create a market failure via an environmental externality. As a result, the first welfare theorem breaks down as the competitive equilibrium does not

[7]The optimality conditions corresponding to the *laissez-faire* equilibrium are derived in Appendix D.

coincide with the social planner's outcome. The externality, measured by the inefficiency wedge ϖ_t, distorts the equilibrium and gives rise to a deadweight loss proportional to v_{Xt}.

3.3 Environmental policy

In the presence of the environmental externality reflected in $\varpi_t > 0$, the social value of carbon differs across agents. This market failure opens the door for government policy to address this externality by ensuring that the *laissez-faire* allocation coincides with that chosen by the social planner. In particular, the government can introduce a tax, τ_t, on GHG emissions to be paid by firms. This policy tool has two interpretations. First, it can be considered as a tax on carbon emissions, in the same spirit as a standard Pigouvian tax that aims to force firms to internalize the social cost of carbon emissions on household utility, thereby correcting the market failure (i.e., the negative externality) by setting the tax equal to the price of carbon emissions.

An alternative interpretation is that the government creates a market for carbon emissions (i.e., a carbon-permits market). Here, the government regulates the quantity of emissions. The optimal value for this instrument can be directly computed from a Ramsey optimal problem. Comparing the social planner's solution to the competitive equilibrium, we make the following proposition:

Proposition 2 *The first-best allocation can be attained by using the instrument τ_t in order to close the inefficiency gap (i.e., $\varpi_t = 0$). This condition is achieved by setting the carbon tax such that:*

$$\tau_t = v_{Xt}.$$

As shown in Appendix D, setting the environmental tax to v_{Xt} ensures that the first-order conditions under the competitive and centralized equilibria coincide. This result is fairly intuitive. In the absence of an environmental policy, abatement reduces profits, and firms will not be willing to bear this cost unless an enforcement mechanism is implemented. The government can impose a price on carbon emissions by choosing the optimal tax (either quantity- or price-based, as discussed in Weitzman, 1974), either a tax or a permit policy would generate revenue that could be used as a "double dividend" to not only correct the externality but also reduce the number of distortions due to the taxation of other inputs, such as labor and capital. Moreover, an equivalence between the tax and permit policies holds when the regulator has symmetric information about all state variables for any outcome under the tax policy and a cap-and-trade scheme (Heutel, 2012).

4 Estimation

In this section, we estimate the structural parameters of the model using Bayesian methods. For a presentation of the method, we refer to the canonical paper of Smets and Wouters (2007). As the U.S. has not implemented any major or county-wide environmental policy, we propose to estimate the *laissez-faire* model. The following subsections discuss the nonlinear method employed for the estimation, the data transformation and calibration, the priors and the posteriors.

4.1 Solution method

To accurately measure higher-order effects of environmental preferences (e.g., precautionary saving, utility curvature), we consider a second-order approximation to the decision rules of our model. Estimating dynamic general equilibrium models using higher-order approximations remains a challenge as the nonlinear filters that are required to form the likelihood function are computationally expensive. An inversion filter has recently emerged as a computationally affordable alternative to apply nonlinear models to data (e.g., Guerrieri and Iacoviello 2017, Atkinson, Richter, and Throckmorton 2020). Initially pioneered by Fair and Taylor (1987), this filter extracts the sequence of innovations recursively by inverting the observation equation for a given set of initial conditions. Unlike other filters (e.g., Kalman or particle),[8] the inversion filter relies on an analytic characterization of the likelihood function. Kollmann (2017) provided the first application of the inversion filter to second- and third-order approximations to the decision rules in a rational-expectations model.[9] To allow the recursion, this filter imposes that the number of fundamental shocks must be equal to the number of observable variables. Note that for linearized models, this restriction is standard following Smets and Wouters (2007). For the relative gains of the inversion filter with respect to a particle filter, we refer to Cuba-Borda, Guerrieri, Iacoviello, and Zhong (2019) and Atkinson et al. (2020).

[8] For a presentation of alternative filters to calculate the likelihood function, see Fernández-Villaverde, Rubio-Ramírez, and Schorfheide (2016).

[9] Kollmann (2017) posits a modified higher-order decision rule in which powers of exogenous innovations are neglected to obtain a straightforward observation equation inversion. In this paper, we include these terms of the decision rule.

The inference is based on five observable macroeconomic time series, which are jointly replicated by the model through the joint realization of five corresponding innovations. Note that we use state-space pruning to characterize the model's nonlinear decision rules, while the matrices of the policy rule are effected using the Dynare package of Adjemian, Bastani, Juillard, Karamé, Maih, Mihoubi, Mutschler, Perendia, Pfeifer, Ratto, and Villemot (2021). From this state-space representation, we reverse the observation equations to obtain the sequence of shocks. Unlike Kollmann (2017) who limits the analysis to a frequentist approach, we augment the likelihood function with prior information in the same spirit as Smets and Wouters (2007). This method requires a sampler, here Metropolis-Hastings, to draw the parametric uncertainty.

4.2 Data

The model is estimated with Bayesian methods on U.S. quarterly data over the sample time period 1973Q1 to 2021Q1, which are all taken from FRED and the U.S. Energy Information Administration.

Concerning the transformation of series, the aim is to map nonstationary data to a stationary model (namely, GDP, consumption, investment, CO_2 emissions, and 3-month Treasury Bill interest rate). Following Smets and Wouters (2007), data exhibiting a trend or unit root are rendered stationary in two steps. We first divide the sample by the working-age population. Second, data are taken in logs, and we apply a first-difference filter to obtain growth rates. Real variables are deflated by the GDP deflator price index, while the T-bill rate is deflated with future growth in inflation rate. The measurement equations mapping our model to the data are given by:

$$\begin{bmatrix} \text{Real Per Capita Output Growth} \\ \text{Real Per Capita Consumption Growth} \\ \text{Real Per Capita Investment Growth} \\ \text{Per Capita } CO_2 \text{ Emissions Growth} \\ \text{Real risk free interest rate} \end{bmatrix} = \begin{bmatrix} \log \gamma^Y + \Delta \log (\tilde{y}_t) \\ \log \gamma^Y + \Delta \log (\tilde{c}_t) \\ \log \gamma^Y + \Delta \log (\tilde{\imath}_t) \\ \log \gamma^X + \Delta \log (\tilde{e}_t) \\ r_t^F \end{bmatrix}, \tag{27}$$

where a variable with a tilda, $\tilde{x}_t$, denotes the detrended version of a level variable, x_t.

4.3 Calibration and prior distributions

The calibrated parameters are reported in Table 5. The calibration of the parameters related to business-cycle theory is standard: the depreciation rate of physical capital is set at 2.5 percent in quarterly terms, the government spending to GDP ratio to 20 percent, the capital intensity α to 0.3, and the share of hours worked per day to 20 percent. The environmental component parameters of the models when not estimated, are set in a similar fashion to Heutel (2012). As in recent DICE models, we set the steady state emissions and real output to match their observed counterparts in 2015 for the U.S., that is, $\bar{e} = 1.35$ Gt and $\bar{y} = 4.55$ trillion USD. This calibration implies a value for the parameter φ_1 of 0.38 as well as a value for the TFP level parameter A of 4.99. The continuation rate of carbon in the atmosphere, denoted η, is set to match an approximately 70-year half time of atmospheric carbon dioxide, consistent with estimates in Nordhaus (1991).[10] The flow of CO_2 emissions e^* from the rest of the world is set to match a steady state stock of carbon of 900 Gt, the latter corresponds to the 2015 value in Nordhaus (2017). Finally, for the abatement-cost function, we set $\theta_1 = 0.05607$ following Heutel (2012) while the curvature parameter $\theta_2 = 2.6$ is taken from the latest version of the DICE model in Nordhaus (2017).

For the remaining set of parameters and shocks, we employ Bayesian methods. Table 6 summarizes the prior — and the posterior — distributions of the structural parameters for the U.S. economy. Let us first discuss the prior for structural disturbances. The prior information on the persistence of the Markov processes and the standard deviation of innovations are taken from Guerrieri and Iacoviello (2017). In particular, the persistence of shocks follows a beta distribution with a mean of 0.5 and a standard deviation of 0.2, while for the standard deviation of shocks, we choose an inverse gamma distribution with mean 0.01 and standard deviation of 1.

As per Smets and Wouters (2007), we estimate the term $(1/\beta - 1) \times 100$ using data on the risk-free rate and impose prior information on this term based on a gamma distribution with a mean of 0.5 and standard deviation 0.25.[11] For the habit parameter m,

[10] To convert a duration into a probability, let us assume that each unit of CO_2 is subject to an idiosyncratic shock, denoted ω, and that the carbon is reused or sequestered in a carbon sink. This random variable is drawn from a binomial distribution, $\omega \sim B(n, p)$ with n being the number of trials and p the probability of success $p = 1 - \tilde{\eta}$. We thus determine the number of trials, n, that are necessary on average for one unit of carbon to be sequestrated. Recall that $E(\omega) = n.p$, and by imposing $E(\omega) = 1$ we calculate that the average number of trials necessary for carbon sequestration is $n = 1/(1 - \tilde{\eta})$. On an annual basis, the latter becomes $n = 0.25/(1 - \tilde{\eta})$. Recall that in the balanced growth path, the effective continuation rate of carbon is $\tilde{\eta} = \eta\gamma^X$. Then, imposing an average half time of carbon of 70, we deduce the value of η as $\tilde{\eta} = (1 - 0.25/70)/\gamma^X$.

[11] Note in addition that our prior mean for $(1/\beta - 1) \times 100$ is much higher than that in Smets and Wouters (2007) as our model is nonlinear and, thus, features the precautionary saving effect that drives down the real rate. With the prior information of Smets and Wouters (2007), we would obtain a real rate below zero; thus, we readjust the prior information to render our nonlinear model consistent with the data.

we impose a less informative prior than Smets and Wouters (2007) to let the data be as informative as possible about the posterior value of this key parameter. We impose a beta distribution with mean 0.5 and standard error 0.15. The elasticity of Tobin's Q to the investment-capital ratio ϵ has the same prior information as in Smets and Wouters (2007) with normal distribution of mean 4 and dispersion of 1.5. This prior actually provides support close to the bound restriction ($1/\epsilon \in [0.16, \infty)$) of the moment matching procedure in Jermann (1998). Regarding deterministic growth rates, the rate of labor-augmenting technological change, which is denoted $(\gamma^Y - 1) \times 100$, follows a Gamma distribution with a prior mean of 0.5 and a standard deviation of 0.1 to match the average 0.40 percent quarterly growth rate. For the (de)coupling rate (denoted $(1-\gamma^E) \times 100$), we consider the same prior information as for the productivity growth rate. Finally, the last remaining parameter is the elasticity of CO_2 emissions to output changes φ_2 and follows a beta distribution with prior mean 0.5 and standard deviation 0.2, this prior is rather uninformative as it only imposes a support between 0 and 1 to be consistent with Heutel (2012).

4.4 Posterior distributions

In addition to prior distributions, Table 6 reports the means and the 5th and 95th percentiles of the posterior distributions drawn from four parallel Markov chain Monte Carlo chains of 50,000 iterations each. The sampler employed to draw the posterior distributions is the Metropolis-Hasting algorithm with a jump scale factor, so to match an average acceptance rate close to 25–30 percent for each chain.

The results of the posterior distributions for each estimated parameter are listed in Table 6 and Figure 2. It is clear from Figure 2 that the data were informative, as the shape of the posterior distributions is very different from the priors. Our estimates of the structural parameters that are common to Smets and Wouters (2007) are mostly in line with those they find. The persistence of productivity and spending shocks are, for instance, very similar to theirs. Regarding the growth rate of productivity, our estimated value, 0.54, is also in line with that in Smets and Wouters (2007). Finally, for the subjective discount rate, denoted $100\,(\beta^{-1} - 1)$, we find a posterior mean of 1.28 that is much higher than that in Smets and Wouters (2007). Relative to their approach, an important difference is that our framework allows for precautionary saving. This effect, which stems from the higher-order terms in the Taylor expansion, in turn affects the estimation of this parameter value. The last remaining parameters are not in common with Smets and Wouters (2007). For the elasticity of Tobin's Q to the investment capital ratio ϵ, we find a posterior mean of 7.15 which is higher than that in Jermann (1998).[12] The value of the elasticity of emissions to output, φ_2, is 0.159, which is very close to the value found in Heutel (2012) based on HP filtered data.

Finally, for the decoupling rate, we find that energy-saving technological change has caused reductions in CO_2 of approximately 2% annually. Regarding the persistence of habits, m, our findings suggest the presence of slow-moving habits with a value for m of 0.978. With this specification, the model reduces to a log utility specification when m is set to 1. As underlined in Jaccard (2014), even for values of m that are close to 1, slow-moving habits in the composite significantly improve the standard models to match asset-pricing facts.

	Mean		Stand. Dev		Corr. w/ output	
	Data [5%;95%]	Model	*Data [5%;95%]*	Model	*Data [5%;95%]*	Model
$100 \times \Delta \log(y_t)$	*[0.21;0.54]*	0.54	*[1.05;1.28]*	1.08	*[1.00;1.00]*	1.00
$100 \times \Delta \log(c_t)$	*[0.28;0.61]*	0.54	*[1.08;1.32]*	1.82	*[0.81;0.90]*	0.82
$100 \times \Delta \log(i_t)$	*[0.08;0.71]*	0.54	*[2.01;2.46]*	1.90	*[0.59;0.78]*	0.50
$100 \times \Delta \log(e_t)$	*[-0.59;0.07]*	-0.08	*[2.11;2.58]*	2.28	*[0.28;0.58]*	0.40
$100 \times r_t^F$	*[0.31;0.51]*	1.06	*[0.61;0.75]*	1.29	*[-0.21;0.16]*	-0.17

Table 1: Data moments vs. model moments (with parameters taken at their posterior mean).

To assess the relevance of the estimated model, as in Jermann (1998), we compare the observable moments taken at a 90 percent interval versus the asymptotic moments generated by the model using a second-order approximation to the policy function. Table 1 reports the results. We find that our model does a reasonably good job at replicating some salient features of the data, as most of the moments simulated by the estimated model fall within the 95 percent confidence interval.

The advantage of using Bayesian estimation is that the model can replicate the historical path of the observable variables that we introduce. Once the shock process parameters have been estimated, it is then possible to simulate the model by drawing shocks from the estimated distribution. As illustrated in Table 1; however, this procedure does not ensure that the unconditional standard deviations observed in the data can be matched. Since

[12] The difference with respect to Jermann (1998) could be explained by the COVID-19 and great financial crisis periods.

this is a potentially important limitation of our analysis, this issue is further discussed in section 6 below.

	Consumption habits	Habits in composite good
Utility function $u(S_t - h_t)$	$S_t = c_t$	$S_t = c_t/x_t$
Prior probability	0.50	0.50
Log marginal data density	2854.53	2934.58
Bayes ratio	1.00000	5.8308e34
Posterior model probability	0.00000	1.00000

Table 2: The comparison of prior and posterior model probabilities in the habits in the composite good vs. consumption habits models (with parameters taken at their posterior mode).

4.5 Habits in the composite good vs. consumption habits

A natural question at this stage is whether our specification of environmental preferences performs better than the standard specification, for example used in Fuhrer (2000). Letting $u(\varepsilon_t^B S_t - h_t)$ denote the utility function and expressing the law of motion of the habit stock in terms of S_t as follows:

$$\gamma^Y h_{t+1} = m h_t + (1-m)\varepsilon_t^B S_t$$

we next test the null hypothesis H_0: $S_t = c_t$ against the alternative H_1: $S_t = c_t/x_t$.

Using an uninformative prior distribution over models (i.e., 50% prior probability for each model), Table 2 shows both the posterior odds ratios and model probabilities taking the standard consumption habit model $\mathcal{M}$ ($S_t = c_t$) as the benchmark. The posterior odds of the null hypothesis is 5e34 to 1. This statistical test leads us to strongly reject the null hypothesis H_0: $S_t = c_t$. The specification of habits is, therefore, more statistically relevant when it is based on the composite good c_t/x_t rather than consumption alone. This result should be qualified, however, as prior distributions were selected here to estimate our model and do not necessarily fit the benchmark model of H_0. This can diminish the empirical performance of the benchmark. Nevertheless, this exercise suggests that our specification is at least as consistent with the data as the standard habits-type model.

5 Results

Our main simulation results appear in Table 3 below. The top panel of this table shows the average level of consumption and the stock of CO_2 emissions, which are denoted by $E(c_t)$ and $E(x_t)$, respectively. The agent's lifetime utility, $E(\mathcal{W}_t)$, is our measure of welfare. The welfare cost measure proposed by Lucas (2003) is denoted by $E(\psi_t)\times 100$. We also report a measure of the welfare cost of uncertainty, which is denoted by $E(\psi_t')\times 100$.

The asset-pricing implications appear in the middle panel, where $400E(r_t^F)$, $400E\left(r_{t+1}^B - r_t^F\right)$, and $std(\hat{\lambda}_t)$ are the mean real risk-free rate, the mean bond premium, expressed in annualized percent, and the standard deviation of marginal utility, respectively.

The bottom panel of Table 3 first lists the share of emissions that firms choose to abate, $E(\mu_t)$. The average cost of abatement is $E(f(\mu_t))$, and $E(\tau_t e_t/y_t)$ is the average cost of the tax borne by firms as a share of GDP.

The first column shows these model implications in the decentralized *laissez-faire* equilibrium with a tax set to zero. Columns (2) to (4) show what happens once the optimal tax is introduced. The optimal policy results are listed for three different values of the parameter θ_1. This latter measures the efficiency of the abatement technology, with higher θ_1 corresponding to a less-efficient technology. As $\theta_1 = 0.056$ is the value that matches the current cost of abatement technologies according to the literature (e.g., Heutel 2012), the results in Column (2) correspond to our baseline scenario.

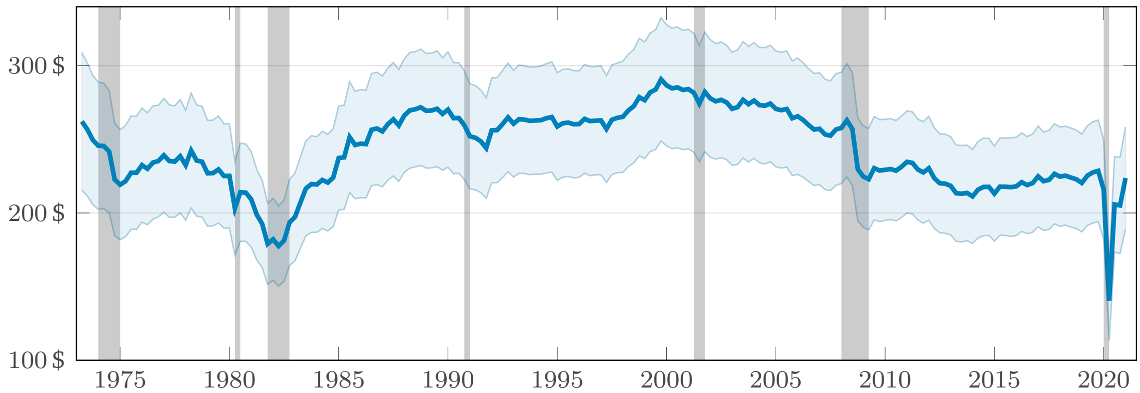
5.1 The size and cyclicality of the optimal tax

The first main takeaway from Table 3 is that a small average carbon tax is sufficient to restore the first-best allocation. In our benchmark scenario, which corresponds to $\theta_1 = 0.056$, the total tax bill is, on average, approximately two percent of GDP (e.g., $E(\frac{\tau_t e_t}{y_t}) = 0.0184$).

As seen by comparing the total tax bill across Columns 2 to 4, in the worst-case scenario, corresponding to a value for θ_1 implying a very inefficient abatement technology, the total tax bill rises to 5.7 percent of GDP. In this adverse scenario, firms only manage to abate approximately 5 percent of all emissions, $E(\mu_t) = 0.0522$, once the tax is introduced.

One advantage of our method is that it can be used to construct counterfactual scenarios. In particular, we can answer the following question: What would the optimal tax τ_t have been in the United States from 1973 to 2021 had this optimal policy been implemented? Figure 1 provides the answer. The optimal tax is time-varying and rises during booms and falls during recessions.

Why is the tax procyclical? Our results suggest that the optimal policy to counter climate change embeds a trade-off between environmental protection and safeguarding the economy. Curbing emissions is costly for the economy, as it comes at the cost of a decline in production. Our theory shows that a carbon tax that is optimally designed takes this dimension into account. Indeed, as shown in Figure 1, the optimal policy should be used to mitigate the effect of severe recessions. For example, it would have been optimal to reduce the carbon tax sharply during the COVID-19 crisis. During booms, in contrast, curbing emissions should be the prime concern. As emissions in the data are strongly procyclical, combating climate change is optimally achieved by raising the carbon tax during expansions. Carbon emitters therefore bear the burden of an increase in taxation during booms, but not during recessions. We further investigate this procyclicality in subsection 5.7, which is devoted to the analysis of impulse responses.



Notes: The simulated path is expressed in levels. The blue shaded area is the parametric uncertainty at the 95% confidence level, drawn from 1,000 Metropolis-Hastings random iterations. The blue line represents the mean of these 1,000 simulated paths. The gray shaded areas are NBER-dated recessions in the U.S. The carbon tax is expressed in U.S. dollars from the model via the expression $-1,000v_{X,t}$.

Figure 1: Historical variations in the environmental tax

5.2 The risk premium and risk-free rate in the laissez-faire equilibrium

As seen in Column (1), the model generates an average bond premium, i.e., $400E\left(r^B_{t+1} - r^F_t\right)$, of approximately 3 percent. Generating a bond premium of this magnitude remains a challenge for a large class of general-equilibrium models with production.

As in Jermann (1998), the positive bond premium that we obtain is due to the interest-rate risk. The price of long-term bonds is determined by the term structure of interest rates. The key is that in this model, short- and long-term interest rates are countercyclical. With interest rates rising during recessions, bond holders can expect capital losses to occur precisely during periods of low consumption and high marginal utility. Long-term bonds are, therefore, not good hedges against consumption risk. The positive bond premium is, thus, compensation for holding an asset whose price declines during periods of low consumption.

In this model, the mean risk-free rate $400E(r_t^F)$ is critically affected by uncertainty. A greater variance in marginal utility reduces the unconditional mean risk-free rate. The intuition is that a higher volatility of marginal utility implies more uncertainty about future valuations, and greater uncertainty in turn increases agents' willingness to build precautionary buffers. Therefore, this effect captures the impact of this precautionary motive on equilibrium interest rates.

Relative to Jermann (1998), an important difference is that we consider a model with more shocks. As illustrated by the variance decomposition in Table 7 below, the technology shock, denoted by σ^A, remains the most important shock for the bond premium. Indeed, a model with technology shocks only would still generate a bond premium of approximately 1.9 percent. In contrast, preference and emissions shocks, which are denoted by σ^B and σ^X, respectively, have a negligible effect on the risk premium. If these two shocks were the only source of business cycle fluctuations, we would obtain a bond premium of a few basis points. For the remaining drivers of the risk premium, the government spending shock σ^G generates a bond premium of approximately 0.6 percent. The investment-specific technology shock σ^I also matters for asset prices, as this shock in isolation generates a bond premium of approximately 0.5 percent.

5.3 Asset prices under the optimal policy

Relative to the *laissez-faire* equilibrium, the optimal tax has a significant effect on the mean risk-free rate. In the baseline scenario, under optimal taxation, our model predicts a rise in the average risk-free rate of approximately 0.9 percentage points. This effect on the risk-free rate can be better understood by comparing the volatility of marginal utility $std(\hat{\lambda}_t)$ in the two cases. One main effect of the tax is to reduce the volatility of marginal utility. Fluctuations in marginal utility provide a measure of uncertainty about future valuations. The lower volatility, therefore, reflects that agents face less uncertainty after the introduction of the tax. The higher mean risk-free rate is due to a reduction in agents' precautionary saving motives.

Since the volatility of marginal utility declines, the risk-free rate is also less volatile under the optimal policy. Holding long-term bonds is therefore less risky because the increase in real interest rates that occurs during recessions under *laissez-faire* becomes more muted. A lower capital loss can, therefore, be expected in crisis times during periods of high marginal utility of consumption. This decline in real interest rate risk then explains the significant decline in the risk premium $400E(r^B_{t+1} - r_{Ft})$ from approximately 3 percent under *laissez-faire* to 1.9 percent once the optimal tax is introduced.

Why is the volatility of marginal utility lower under the optimal policy? As we discuss in the next subsection, the key is that the welfare cost of business cycle fluctuations declines once the optimal tax is introduced. This effect is mainly due to the additional adjustment margin that is activated by the optimal tax. Indeed, whereas the abatement technology plays no role in the *laissez-faire* equilibrium, the optimal tax creates an incentive to use intensively the abatement technology to circumvent the effect of the carbon tax on profits. Introducing an additional adjustment margin in turn facilitates consumption smoothing of the composite good, as the abatement technology can be used to choose a trajectory for the stock of emissions that is optimal from a welfare perspective. In contrast, as the evolution of the stock of emissions is taken as given under *laissez-faire*, consumption smoothing of the composite good is more difficult to achieve, which in turn gives rise to larger fluctuations in marginal utility.

5.4 Welfare analysis

To assess the welfare implications of the optimal policy, Table 3 also shows agents' lifetime utility $E\left(\mathcal{W}_t\right)$, where:

$$\mathcal{W}_t = E_0 \left\{ \sum_{t=0}^{\infty} \beta^t \log\left(\varepsilon^B_t c_t / x_t - h_t\right) \right\}$$

The value of $E\left(\mathcal{W}_t\right)$ is compared. across Columns (1) and (2), the policy generates a sizeable rise in welfare. This substantial welfare gain illustrates that the fall in the stock of emissions $E(x_t)$ more than compensates for the lower average consumption that the tax produces. This measure, however, does not capture the effect of uncertainty on welfare.

Following Lucas (2003), we also compute the welfare cost of the business cycle fluctuations. Since we consider a richer specification, in our economy, the welfare cost can be calculated from the following condition: $E(\mathcal{W}_t) = \log\left((1-\psi_t)\,\bar{c}/\bar{x} - \bar{h}\right) / (1-\beta)$, where ψ_t can be interpreted as the fraction of consumption that households would be willing to abandon to live in a world without any business cycle fluctuations.[13] As shown in Table 3, under *laissez-faire*, we obtain a measure of welfare cost, denoted $E(\psi_t) \times 100$, of 3.8 percent per quarter. Under the optimal policy and for our benchmark scenario, this welfare cost declines from 3.8 to 3.1 percent. However, the welfare cost that we obtain is considerably higher than that obtained by Lucas (2003) in an endowment economy, and remains in the lower range of what is typically reported in asset pricing studies (see, for example, Barlevy (2005)).

We also report a measure of the welfare cost of uncertainty by comparing average welfare, i.e., $E(\mathcal{W}_t)$ in the stochastic economy with the deterministic case, $\overline{\mathcal{W}}$. Since uncertainty harms agents, the difference between the two measures provides an indication of the decline in welfare, expressed in percentage terms, caused by the presence of aggregate risk. In Table 3, this measure is denoted by $E(\psi_t') \times 100$. The decline from 2.7 to 2.3 percent once the optimal tax is introduced confirms that the optimal policy reduces the adverse effect of uncertainty on welfare.

The welfare and asset pricing implications critically depend on the elasticity of emissions to a change in the tax. As this elasticity depends on firms' willingness to reduce emissions, we next discuss the role of abatement technology.

5.5 *The role of abatement technology*

In Table 3, the purpose of Columns (3) and (4) illustrates that the effect of the optimal tax critically depends on the efficiency of the abatement technology. In the *laissez-faire* equilibrium, the externality not being internalized leads firms to spend nothing on abatement. By forcing firms to internalize the externality, the tax incentivizes firms to use the abatement technology to reduce the burden of the tax.

In our preferred scenario, approximately 66 percent of emissions are abated once the optimal tax is introduced. As shown in the bottom panel of Table 3, when θ_1 is above 0.056, less-efficient technology reduces the share of emissions abated $E(\mu_t)$. Note that as abatement-technology efficiency declines, the planner also chooses to allocate a larger fraction of resources to consumption. This reflects that this model embeds a trade-off between consumption and abatement technology. The marginal cost of renouncing a unit of consumption should equal the marginal benefit from abating one unit of emissions. Consequently, the planner finds it optimal to allocate more resources to consumption as abatement-technology efficiency falls.

[13] This result has benefited from suggestions by an anonymous referee.

	Laissez-faire	Optimal policy		
	Estimated Model	$\theta_1 = 0.056$	$\theta_1 = 0.288$	$\theta_1 = 3.500$
	(1)	(2)	(3)	(4)
Business-cycle variables				
$E\left(c_t\right)$ *consumption*	2.5952	2.4692	2.5611	2.5848
$E\left(x_t\right)$ *carbon stock*	933.51	660.40	843.93	906.70
$E\left(\mathcal{W}_t\right)$ *welfare*	-604.69	-580.16	-597.38	-602.44
$E\left(\psi\right) \times 100$ *welfare cost Lucas*	3.8017	3.1056	3.5995	3.6908
$E\left(\psi'\right) \times 100$ *welfare cost of uncertainty*	2.7285	2.2767	2.5995	2.6502
Asset-pricing implications				
$400E\left(r_t^F\right)$ *risk free rate*	4.2599	5.1553	4.5485	4.3296
$400E\left(r_{t+1}^B - r_t^F\right)$ *risk premium*	3.0357	1.9287	2.6745	2.9551
$std(\hat{\lambda}_t)$ *SE marginal utility cons.*	0.7979	0.7442	0.7869	0.7996
Abatement technology				
$E\left(\mu_t\right)$ *abatement share*	0.0000	0.6635	0.2089	0.0522
$E\left(f(\mu_t)\right)$ *abat. cost to gdp*	0.0000	0.0236	0.0060	0.0014
$1000E(\tau_t)$ *tax in USD per Gt*	0.0000	271.8	219.3	206.5
$E(\tau_t e_t/y_t)$ *tax revenues to gdp*	0.0000	0.0184	0.0490	0.0571

Notes: The first column is the estimated model under the *laissez-faire* equilibrium, with no abatement and no environmental tax. Column (2) is the equilibrium under an environmental tax with θ_1 set as in the literature. Columns (3) and (4) are equilibria under alternative values of θ_1 that match an abatement share $\bar{\mu}$ of 20% and 5%. Note that $E(\mu_t) \neq \bar{\mu}$ in Columns (3) and (4), due to the contribution of future shocks to the asymptotic mean of these variables.

Table 3: In Column (1), the model simulations correspond to the *laissez-faire* equilibrium. The simulations under the optimal environmental policy are shown in Columns (2) to (4). Columns (2) to (4) correspond to different abatement costs, ranging from low to high.

As seen by comparing our two welfare cost measures, i.e., $E(\psi_t) \times 100$ and $E(\psi_t') \times 100$ across Columns (2) to (4), the size of the welfare gain relative to the *laissez-faire* equilibrium depends critically on the abatement technology. This illustrates that the distortion caused by the tax can be sizable if the technology is not sufficiently well-developed. If emissions are costly to abate, the policy has a stronger negative impact on production, as it is more difficult for firms to circumvent the tax. In this case, the tax generates a smaller drop in emissions, which in turn reduces the policy's welfare gains.

Comparing the effect of the optimal tax on $400E\left(r_t^F\right)$ and $400E\left(r_{t+1}^B - r_t^F\right)$, the effect on asset prices also depends crucially on θ_1. Relative to the first-best scenario, the effect of the tax on the risk premium is more muted when the abatement technology is less efficient.

This illustrates that the reduction in uncertainty achieved by the policy is due to the additional margin provided by the abatement technology. The effect of θ_1 is akin to the adjustment-cost parameter in Jermann (1998). The more efficient the abatement technology, the easier it is for agents to insure against unexpected shocks. This greater flexibility makes the economy less risky from consumption smoothing perspective, which reduces the risk premium and increases the risk-free rate, as the need for precautionary saving becomes less pressing.

5.6 Climate policy and asset prices with standard preferences

In many models, the EIS mainly affects quantities, whereas asset pricing implications are driven by risk aversion (e.g., Cochrane 2017; Tallarini 2000). In contrast, the financial and macroeconomic implications of our model are tightly linked. Our preference specification creates this interaction between finance and the environmental policy. This point is illustrated in Table 9, which studies the effect of the optimal policy on the mean risk-free rate, the risk premium, and the volatility of marginal utility in a version of the model without habit formation. When m is set to 1, our model reduces to the case with log utility:

$$\mathcal{W}_t = E_0 \sum_{t=0}^{\infty} \beta^t \left[\log\left(\varepsilon_t^B\right) + \log\left(c_t\right) - \log(x_t)\right]$$

Without habits, the model is no longer able to generate a realistic risk premium in the *laissez-faire* equilibrium. Relative to the habit model, the risk premium falls from approximately 3 percent to essentially 0. In this case, the dichotomy between climate policies and finance is also close to perfect. Indeed, as illustrated in Table 9 the introduction of the optimal tax essentially has no effect on the risk-free rate and risk premium. In a model that fails to reproduce risk premiums of a realistic magnitude, one may therefore be tempted to conclude that climate risk and environmental policies have a negligible effect on financial markets.

The results reported in Table 9 correspond to the log utility case. One natural question to ask is whether more realistic asset pricing implications can be obtained by simply increasing the coefficient or relative risk aversion via the curvature parameter. When we try to increase the coefficient of relative risk aversion from 1 to 20, we find that increasing curvature has a negligible impact on the risk premium but generates a very large increase in the mean risk-free rate. With a high curvature coefficient, the optimal policy also has no effect on the model's asset-pricing implications. Therefore, the dichotomy between climate policies and finance cannot be broken by a very high value of the curvature coefficient.

5.7 *The responses to shocks*

Figure 3 compares the response of output (y), consumption (c), investment (i), and abatement (μ) in the *laissez-faire* equilibrium with the optimal policy. As seen on the lower-left chart of this figure, the response of investment is more muted under the optimal policy. Once the optimal tax is implemented, as the lower-right chart shows, this smaller response of investment is compensated by an increase in abatement expenditures, as firms reallocate resources from capital accumulation to emissions abatement. This reallocation of resources illustrates the main mechanism at work. Once the optimal policy is introduced, firms find it optimal to use the abatement technology to reduce the burden of the tax. In contrast, this adjustment margin is not used under *laissez-faire*.

As can be seen by comparing the red crosses to the green circles in the upper-right panel, another key difference is that the response of consumption on impact is more muted under the optimal policy. Under the optimal policy, firms internalize the externality by shifting resources from investment to abatement. Although the investment margin is used less intensively, the optimal policy still leads to a reduction in consumption volatility. This illustrates that under our benchmark scenario, which assumes that efficient abatement technology is available, consumption smoothing is best achieved by combining the investment and climate mitigation margins.

Relative to the *laissez-faire equilibrium*, this decline in investment reduces capital accumulation. This difference in capital accumulation in turn explains the slightly more muted response of output depicted in the upper-left panel. Since labor is fixed, the quantitative magnitude of this effect on output is small, however.[14]

Figure 4 further deconstructs the mechanism by plotting the response of the optimal tax (τ), emissions (e), the marginal cost of production (ϱ) and Tobin's Q (q). The upper-left panel depicts the response of the optimal tax, which is constant and equal to zero in the *laissez-faire* equilibrium. As Heutel (2012) or Golosov et al. (2014), the optimal tax is procyclical when the economy is hit by a technology shock. However, the origin here of this procyclicality differs. Indeed, in standard climate policy models, the tax reflects the discounted sum of output losses from climate change and is therefore proportional to output. In this paper, the tax is also proportional to output (as a result of future utility

[14]Simultaneously, our main result, i.e., the effect of the optimal policy on the risk premium and the real rate, is robust to the introduction of endogenous labor supply (e.g., Jaccard, 2014)

losses), but its dynamics is mainly driven by fluctuations in the SDF.[15] The tax is also substantially more volatile than that obtained in Heutel (2012).

To illustrate the role of the SDF on the optimal tax, which we derived in equation (23), Table 8 isolates the respective contributions of the different components of this formula, namely, consumption, the stock of emissions, and the SDF in the case of technology shocks. When the economy is experiencing a TFP-driven boom, the decline in real interest rates increases the present value of future damages via a discounting effect. In a model that generates a 3 percent bond premium, and as shown in Table 8, this discounting effect explains 70 percent of the short-term fluctuations of the tax, and 50 percent of its medium-term fluctuations. The remaining fraction is explained by the marginal damage term, which depends on consumption as well as the stock of emissions. However, since the stock of emissions moves very slowly over the cycle, its contribution to the time variation of the optimal tax is very small.

As illustrated by the right-hand side of Table 8, without habits, the SDF only explains approximately 5 and 6 percent of the short- and medium-term fluctuations in the tax, respectively. At the same time, as discussed above, without habits, the model is no longer able to generate a risk premium of a realistic magnitude. This illustrates the key difference between our approach and that of Heutel (2012) or Golosov et al. (2014), for example. Indeed, the procyclical variations in the tax that we obtain are mainly due to fluctuations in the SDF and not to variations in the output loss caused by climate change.

The upper-right panel compares the response of emissions in the *laissez-faire* equilibrium with the optimal allocation. Whereas emissions are procyclical under *laissez-faire*, emissions decline during booms once they are taxed by the government. The strong increase in abatement effort, which in turn reduces emissions, can be explained by the procyclicality of the optimal tax. As firms aim to reduce the burden of the optimal tax, they find it optimal to strongly increase abatement expenditures during booms.

The mechanism via which the optimal tax reduces the volatility of investment works through the marginal productivity of capital. This effect can be illustrated by analyzing the effect of the optimal policy on equation (18). Whereas the marginal cost ϱ is constant in the *laissez-faire equilibrium,* this term declines during boom periods under the optimal policy. By reducing the increase in the marginal productivity of capital in response to positive technology shocks, this effect, in turn, attenuates the response of investment.

Finally, as shown by the lower-right panel, this joint effect of the optimal tax on the

[15] As noted by Heutel (2012), an increase in output also increases the opportunity cost of abatement (as long as $\varphi_2 < 1$), but this effect is counterbalanced by the tax hike.

SDF and marginal productivity of capital in turn reduces the volatility of Tobin's Q. The next section further studies the implications of the optimal policy for the price of capital by considering a version of the model that reproduces a 6 percent equity premium in the *laissez-faire* equilibrium.

The effects of preference, government spending and emission shocks on macroeconomic and environmental variables are discussed in Appendix G.

6 Robustness checks

This section discusses two robustness checks. First, asset-pricing models are usually evaluated in terms of their ability to reproduce a 6 percent equity premium, as well as a low mean risk-free rate (e.g., Mehra and Prescott, 1985), whereas in the previous section, we focused on the bond premium. Reproducing the volatility of macroeconomic aggregates, such as consumption, is also an important test for this class of models.

Second, since we use a solution method that is relatively novel, we compare it to other nonlinear methods that are more widely used in the literature. This comparison is shown in Appendix H.

6.1 Matching the moments

As seen in Table 1, the model overstates the volatility of consumption, which is more volatile than output when the model is simulated. We also have a risk-free rate puzzle (e.g., Weil, 1989), as the mean risk-free rate that we obtain is too high relative to the data. In this section, we study the effects of the optimal tax in a version of the model that is able to reproduce these facts.

The equity premium puzzle

Following Jermann (1998), Abel (1999) and Gomes and Schmid (2010) among others, we introduce leverage by allowing firms to issue nondefaultable short-term debt, which is denoted by b^F. The price at which short-term debt is issued is denoted by p_B^F. Issuing debt is costly and firms have to pay a fixed cost of issuance, which we denote by ι, that is proportional to the amount of new debt issued in period t. The introduction of leverage affects the maximization problem of the firm, and dividends are given as follows:

$$d_t = y_t - w_t n_t - i_t - f(\mu_t) y_t - e_t \tau_t + p_{Bt}^F b_{t+1}^F - b_t^F - \iota b_{t+1}^F.$$

Relative to the previous section, leverage adds the following optimality: condition in the problem of the representative firm:

$$p_{Bt}^{F} = \beta E_t \frac{\lambda_{t+1}}{\lambda_t} + \iota$$

We introduce a demand by assuming that households prefer corporate debt. This constraint is meant to capture the notion that household also value the services provided by assets that pay a fixed payoff. This preference for safe corporate short-term debt is modeled by introducing the following inequality constraint into the household maximization problem[16]:

$$b_{t+1}^{F} \geq \varkappa \tag{28}$$

where $\varkappa$ is the preference for debt parameter. Combining the optimality conditions with respect to the corporate debt of households and firms in turn implies that:

$$\zeta_t = \lambda_t \iota$$

where ζ is the Lagrange multiplier associated with the preference for debt constraint in the optimization problem of the representative household. As we discuss below, the issuance cost parameter ι is set to a very small but positive value. In equilibrium, the rate of return on short-term corporate debt is therefore equivalent to the risk-free rate. Since for plausible parameter values, marginal utility is always strictly positive in this model, and given a small but positive value for ι, the constraint (28) is always strictly binding.[17]

Moment matching exercise

Relative to the previous section, the introduction of leverage adds two additional degrees of freedom, namely, the cost of issuance ι and the level of debt $\varkappa$. Given the lack of information regarding this parameter, and since it only plays a marginal role, we set the cost of issuance ι to 0.0001. This is to ensure that this parameter has essentially no effect on our results.[18] Since it has an important impact on the dynamics of dividends, and, hence, on the equity premium, the preference parameter $\varkappa$ is chosen to maximize

[16] Introducing debt into the utility function would be another way to close the model.

[17] We checked that marginal utility is always strictly positive by simulating a sample of 50,000 periods using a fourth-order approximation to the policy function.

[18] At the same time, a positive value for ι is necessary to ensure that the constraint (28) is always strictly binding.

the model's ability to reproduce a realistic equity premium.

Given that our approach builds on Jermann (1998), we follow a similar strategy and use the simulated method of moments to minimize the distance between a set of empirical facts and the corresponding simulated moments produced by the model.

Following Jermann (1998), the five moments to match are the standard deviations of output, consumption, and investment, which in Table 4 are expressed in growth rates, as well as the mean risk-free rate and equity premium. The last two moments are expressed in annualized percent. Since the model dynamics critically depend on the allocation of output between consumption and investment, we also include the average consumption to output ratio, i.e., $E(c/y)$, into the list of moments to match.

As in Jermann (1998), the first 5 parameters selected to maximize the model's ability to reproduce these moments are (i) the adjustment-cost parameter, $1/\epsilon$; (ii) the habit parameter, m; (iii) the subjective discount factor, β; (iv) the technology-shock standard deviation, σ_A; and (v) the shock-persistence parameter, ρ_A. Relative to Jermann (1998), we add the new parameter that we have introduced, namely, the preference for debt coefficient $\varkappa$. The loss function is minimized for the following set of parameters:

Calibrated Parameters

ϵ	m	β	σ_A	ρ_A	$\varkappa$
0.26	0.9	0.987	0.0076	0.999	4.5

Following standard practice in the asset pricing literature, the model's implications are compared to the data. In Table 4, the first column shows the estimated moments for the standard deviations of output, consumption, and investment. The risk-free rate mean and standard deviation, as well as the mean equity premium are annualized and are denoted by $400E(r_t^F)$, $400std(r_t^F)$, and $400E(r_{t+1}^E - r_t^F)$, respectively. As in the previous section, we assume that the American economy corresponds to the *laissez-faire* equilibrium.

As seen by comparing Column (2) with the data in Column (1), the model is able to reproduce the 6 moments that were targeted. As shown in the lower part of the table, which reports moments that were not targeted, the model generates movements in the risk-free rate that are too volatile. Compared to Jermann (1998), combining slow-moving habits with leverage, nevertheless, allows us to decrease the risk-free rate standard deviation from 11.5 to 4.7 percent. Such a value for the risk-free rate standard deviation seems plausible, as it is below that computed by Jordà, Knoll, Kuvshinov, Schularick, and Taylor (2019), using long samples of historical data, as well as a large set of countries.

	(1)	(2)	(3)
	Data USA (1973-2019)	Laissez-faire Economy	Optimal Policy
Targeted moments			
$std(y_t)$	0.8	0.8	0.8
$std(c_t)$	0.4	0.5	0.4
$std(i_t)$	2.0	2.1	1.5
$400E(r_t^F)$	0.7	0.7	2.2
$400E(r_{t+1}^E - r_t^F)$	6.0	6.0	4.0
$E(c_t/y_t)$	0.57	0.55	0.55
Nontargeted moments			
$400std(r_t^F)$	2.5	4.7	3.4
$E(\mu_t)$	0	0	0.55
$100E(\psi_t)$	N/A	0.3	0.0
$100E(\psi_t')$	N/A	0.9	0.2

Table 4: Outcomes from the Simulated Moments Matching method.

The third column of Table 4 lists the simulated moments when the optimal tax is introduced. Under the optimal tax, the efficiency of the abatement technology parameter θ_1 is calibrated to imply a share of emission abatement, i.e., $E(\mu)$, of 55 percent. This is achieved by setting a value for θ_1 of 0.12. The moments generated by the model in Column (3) correspond to a scenario in which the abatement technology is slightly less efficient than under our benchmark scenario (see Table 3). Under this calibration, the introduction of the optimal tax leads to an abatement effort of 55 percent, which is the target fixed by the Paris Agreement for 2030. Relative to the *laissez-faire* equilibrium shown in Column (2), all other parameters values remain unchanged.

Comparing the *laissez-faire* economy with the optimal tax case, we found that the equity premium declines from 6 to 4 percent. The mean risk-free rate triples and increases from 0.7 to 2.2 percent. The effect on investment is also sizeable, as the investment standard deviation declines from 2.1 to 1.5 percent.

The last two lines of Table 4 report our measures of welfare cost of business cycle fluctuations and uncertainty, which are denoted by $100E(\psi_t)$ and $100E(\psi_t')$, respectively. Relative to the *laissez-faire* equilibrium, the introduction of the optimal tax significantly reduces these two measures. This confirms that, in this version of the model as well, the decline in the risk premium and the increase in the risk-free rate are due to the reduction in aggregate risk induced by the optimal policy. The optimal tax has a stabilizing effect on the economy. In our general equilibrium model, this stabilizing effect, which is obtained by correcting the externality, in turn reduces the compensation required by investors to hold risky assets and reduces the need for precautionary saving.

In summary, the optimal tax also has significant asset pricing implications in a version of the model that is calibrated following standard practice in the literature. In particular, this version of the model not only reproduces the fact that consumption is half as volatile as output but also the low mean risk-free rate as well as the sizeable equity premium observed in the data, without generating fluctuations in the risk-free rate that are excessive.

7 Conclusion

Drawing from the macroeconomic, financial, and environmental literature, this paper introduces an environmental externality into the neoclassical growth model. Our first main takeaway is that the optimal carbon tax is determined by the implicit price of CO_2 emissions. We then show how to use asset-pricing theory to estimate the optimal carbon tax over the business cycle.

In our economy, the welfare cost of business cycle fluctuations is higher when firms do not internalize the damage caused by emissions. We show that the uncertainty induced by the environmental externality raises risk premia and lowers the natural rate of interest by increasing precautionary saving. In the *laissez-faire* equilibrium, the key is that a fraction of the variations in the marginal utility of consumption induced by the externality are excessive. The optimal policy therefore eliminates the fluctuations that are inefficient. These more stable fluctuations have financial market implications, as risk premiums decline and the risk-free real rate increases once the environmental tax is implemented.

The main policy implication is that the effectiveness of the policy critically depends on the abatement technology, so that policy success may depend on the timing of implementation. Clearly, improving the existing emission abatement technology should come first. Once available, an efficient technology would help mitigate the side effects of the tax, thereby maximizing the welfare gains from the policy.

As our study focuses primarily on tax policy, future research could investigate how a permits market could affect asset prices and welfare, either by considering the case of asymmetric information,[19] or by developing a framework where both households and

[19] Asymmetric information breaks the equivalence between the tax and the permit policy (Heutel 2012).

firms are affected by the externality. This type of framework would allow for multipolicy evaluation, such as the comparison of tax and cap-and-trade policies.

Another important limitation of our analysis is that the deterministic growth rate of the economy is given exogenously. In contrast, the abatement choice is endogenously determined, and as we are primarily interested in the cyclicality of the carbon tax, our analysis focuses on business-cycle frequency. Addressing this question in a unified framework in which long-term growth and business cycle fluctuations can be jointly analyzed would be a major step forward.

We also restrict our analysis to the case of a representative agent economy, and do not study the effect of the carbon tax on wealth distribution. Understanding the distributive implications of environmental policies is another important avenue for further research (e.g., Benmir and Roman, 2022).

Finally, one main takeaway from our analysis is that the optimal carbon tax should vary substantially over the cycle. In practice, however, constraints related to political economy considerations or the difficulty in assessing the state of the economy in real time could make the optimal policy difficult to implement. One possible solution would be to delegate this function to an independent institution such as a carbon central bank.[20]

[20]See J. Delpla and C. Gollier "Pour une Banque centrale du carbone", Les Echos, October 2019.

8 Bibliography

A. B. Abel. Asset Prices under Habit Formation and Catching Up with the Joneses. *American Economic Review*, 80(2):38–42, May 1990. URL https://ideas.repec.org/a/aea/aecrev/v80y1990i2p38-42.html.

A. B. Abel. Risk premia and term premia in general equilibrium. *Journal of Monetary Economics*, 43(1):3–33, February 1999. URL https://ideas.repec.org/a/eee/moneco/v43y1999i1p3-33.html.

D. Acemoglu, P. Aghion, L. Bursztyn, and D. Hemous. The environment and directed technical change. *American Economic Review*, 102(1):131–66, 2012. URL https://EconPapers.repec.org/RePEc:cpr:ceprdp:8660.

S. Adjemian, H. Bastani, M. Juillard, F. Karamé, J. Maih, F. Mihoubi, W. Mutschler, G. Perendia, J. Pfeifer, M. Ratto, and S. Villemot. Dynare: Reference manual version 4. (1), 2021. URL https://EconPapers.repec.org/RePEc:cpm:dynare:001.

M. M. Andreasen. An estimated DSGE model: Explaining variation in nominal term premia, real term premia, and inflation risk premia. *European Economic Review*, 56 (8):1656–1674, 2012. doi: 10.1016/j.euroecorev.2012. URL https://ideas.repec.org/a/eee/eecrev/v56y2012i8p1656-1674.html.

T. Atkinson, A. W. Richter, and N. A. Throckmorton. The zero lower bound and estimation accuracy. *Journal of Monetary Economics*, 115:249–264, 2020. URL https://EconPapers.repec.org/RePEc:eee:moneco:v:115:y:2020:i:c:p:249-264.

M. Baker, D. Bergstresser, G. Serafeim, and J. Wurgler. Financing the response to climate change: The pricing and ownership of u.s. green bonds. NBER Working Papers 25194, National Bureau of Economic Research, Inc, 2018. URL https://EconPapers.repec.org/RePEc:nbr:nberwo:25194.

R. Bansal and A. Yaron. Risks for the long run: A potential resolution of asset pricing puzzles. *The Journal of Finance*, 59(4):1481–1509, 2004. URL https://EconPapers.repec.org/RePEc:nbr:nberwo:8059.

R. Bansal, D. Kiku, and M. Ochoa. Climate change risk. *Mimeo, Duke University*, 2019. URL https://www.frbsf.org/economic-research/wp-content/uploads/sites/4/Paper-5-2019-11-8-Kiku-1PM-1st-paper.pdf.

G. Barlevy. The cost of business cycles and the benefits of stabilization. *Economic Perspectives*, 29(Q I):32–49, 2005. URL https://ideas.repec.org/a/fip/fedhep/y2005iqip32-49nv.29no.1.html.

M. Barnett, W. Brock, L. P. Hansen, and H. Hong. Pricing Uncertainty Induced by Climate Change. *Review of Financial Studies*, 33(3):1024–1066, 2020. URL https://ideas.repec.org/a/oup/rfinst/v33y2020i3p1024-1066..html.

M. Barnett, W. Brock, and L. P. Hansen. Climate Change Uncertainty Spillover in the Macroeconomy. In *NBER Macroeconomics Annual 2021, volume 36*, NBER Chapters. National Bureau of Economic Research, Inc, November 2021. URL https://ideas.repec.org/h/nbr/nberch/14556.html.

L. Barrage. Optimal dynamic carbon taxes in a climate–economy model with distortionary fiscal policy. *The Review of Economic Studies*, 87(1):1–39, 2020. URL https://EconPapers.repec.org/RePEc:oup:restud:v:87:y:2020:i:1:p:1-39.

M. D. Bauer and G. D. Rudebusch. The Rising Cost of Climate Change: Evidence from the Bond Market. *The Review of Economics and Statistics*, pages 1–45, 09 2021. ISSN 0034-6535. doi: 10.1162/rest_a_01109. URL https://doi.org/10.1162/rest_a_01109.

G. Benmir and J. Roman. The Distributional Costs of Net-Zero: A HANK Perspective. Mimeo, 2022. URL https://ghassanebenmir.com/files/job-market-paper.pdf.

Y. Cai and T. S. Lontzek. The social cost of carbon with economic and climate risks. *Journal of Political Economy*, 127(6):2684–2734, 2019. URL https://EconPapers.repec.org/RePEc:arx:papers:1504.06909.

J. Y. Campbell and J. H. Cochrane. By force of habit: A consumption-based explanation of aggregate stock market behavior. *Journal of Political Economy*, 107(2):205–251, 1999. URL https://EconPapers.repec.org/RePEc:hrv:faseco:3119444.

L. J. Christiano, R. Motto, and M. Rostagno. Risk shocks. *American Economic Review*, 104(1):27–65, 2014. URL https://EconPapers.repec.org/RePEc:nbr:nberwo:18682.

J. Cochrane. Macro-finance. *Review of Finance*, 21(3):945–985, 2017. URL https://EconPapers.repec.org/RePEc:oup:revfin:v:21:y:2017:i:3:p:945-985.

J. H. Cochrane. Presidential address: Discount rates. *The Journal of Finance*, 66(4): 1047–1108, 2011.

J. H. Cochrane and L. P. Hansen. Asset Pricing Explorations for Macroeconomics. In *NBER Macroeconomics Annual 1992, Volume 7*, NBER Chapters, pages 115–182. National Bureau of Economic Research, Inc, November 1992. URL https://ideas.repec.org/h/nbr/nberch/10992.html.

G. M. Constantinides. Habit Formation: A Resolution of the Equity Premium Puzzle. *Journal of Political Economy*, 98(3):519–543, June 1990. doi: 10.1086/261693. URL https://ideas.repec.org/a/ucp/jpolec/v98y1990i3p519-43.html.

P. Cuba-Borda, L. Guerrieri, M. Iacoviello, and M. Zhong. Likelihood evaluation of models with occasionally binding constraints. *Journal of Applied Econometrics*, 34(7):1073–1085, 2019. URL https://EconPapers.repec.org/RePEc:fip:fedgfe:2019-28.

I. Dew-becker. Bond pricing with a time–varying price of risk in an estimated medium–scale bayesian dsge model. *Journal of Money, Credit and Banking*, 46(5):837–888, 2014. URL https://EconPapers.repec.org/RePEc:wly:jmoncb:v:46:y:2014:i:5:p:837-888.

S. Dietz and F. Venmans. Cumulative carbon emissions and economic policy: in search of general principles. *Journal of Environmental Economics and Management*, 96:108–129, 2019. URL https://EconPapers.repec.org/RePEc:eee:jeeman:v:96:y:2019:i:c:p:108-129.

S. Dietz, F. van der Ploeg, A. Rezai, and F. Venmans. Are economists getting climate dynamics right and does it matter? *Journal of the Association of Environmental and Resource Economists*, 8(5):895–921, 2021. URL https://EconPapers.repec.org/RePEc:ucp:jaerec:doi:10.1086/713977.

A. Eliet-Doillet and A. Maino. Can unconventional monetary policy contribute to climate action? Swiss Finance Institute Research Paper Series 22-35, Swiss Finance Institute, 2022. URL https://EconPapers.repec.org/RePEc:chf:rpseri:rp2235.

L. G. Epstein and S. E. Zin. Substitution, risk aversion, and the temporal behavior of consumption and asset returns: A theoretical framework. *Econometrica*, 57(4):937–969, 1989. URL https://EconPapers.repec.org/RePEc:ucp:jpolec:v:99:y:1991:i:2:p:263-86.

R. Fair and J. Taylor. Solution and maximum likelihood estimation of dynamic nonlinear rational expectations models. *Econometrica*, 51:1169–1185, 1987. URL https://EconPapers.repec.org/RePEc:nbr:nberte:0005.

J. Fernández-Villaverde and J. F. Rubio-Ramírez. Estimating dynamic equilibrium economies: linear versus nonlinear likelihood. *Journal of Applied Econometrics*, 20 (7):891–910, 2005.

J. Fernández-Villaverde and J. F. Rubio-Ramírez. Estimating macroeconomic models: A likelihood approach. *Review of Economic Studies*, 74(4):1059–1087, 2007. URL https://EconPapers.repec.org/RePEc:cpr:ceprdp:5513.

J. Fernández-Villaverde, J. F. Rubio-Ramírez, and F. Schorfheide. Solution and estimation methods for DSGE models. In *Handbook of Macroeconomics*, volume 2, pages 527–724. Elsevier, 2016. URL https://EconPapers.repec.org/RePEc:eee:macchp:v2-527.

C. Fischer and M. Springborn. Emissions targets and the real business cycle: Intensity targets versus caps or taxes. *Journal of Environmental Economics and Management*, 62(3):352–366, 2011. doi: 10.1016/j.jeem.2011.04.00. URL https://ideas.repec.org/a/eee/jeeman/v62y2011i3p352-366.html.

S. Fried. Seawalls and Stilts: A Quantitative Macro Study of Climate Adaptation. *The Review of Economic Studies*, 12 2021. ISSN 0034-6527. doi: 10.1093/restud/rdab099. URL https://doi.org/10.1093/restud/rdab099. rdab099.

J. C. Fuhrer. Habit formation in consumption and its implications for monetary-policy models. *American Economic Review*, 90(3):367–390, June 2000. doi: 10.1257/aer.90.3.367. URL https://www.aeaweb.org/articles?id=10.1257/aer.90.3.367.

S. Giglio, B. T. Kelly, and J. Stroebel. Climate Finance. NBER Working Papers 28226, National Bureau of Economic Research, Inc, Dec. 2020. URL https://ideas.repec.org/p/nbr/nberwo/28226.html.

C. Gollier. The cost-efficiency carbon pricing puzzle. Working Paper 15919, CEPR, 2021. URL https://EconPapers.repec.org/RePEc:cpr:ceprdp:15919.

M. Golosov, J. Hassler, P. Krusell, and A. Tsyvinski. Optimal taxes on fossil fuel in general equilibrium. *Econometrica*, 82(1):41–88, 2014. URL https://EconPapers.repec.org/RePEc:cpr:ceprdp:8527.

J. Gomes and L. Schmid. Levered returns. *The Journal of Finance*, 65(2):467–494, 2010. doi: https://doi.org/10.1111/j.1540-6261.2009.01541.x. URL https://onlinelibrary.wiley.com/doi/abs/10.1111/j.1540-6261.2009.01541.x.

F. Gourio and C. Fries. Adaptation and the Cost of Rising Temperature for the U.S. Economy. Working Paper Series WP 2020-08, Federal Reserve Bank of Chicago, 2020. URL https://ideas.repec.org/p/fip/fedhwp/87687.html.

L. Guerrieri and M. Iacoviello. Collateral constraints and macroeconomic asymmetries. *Journal of Monetary Economics*, 90:28–49, 2017. URL https://EconPapers.repec.org/RePEc:eee:moneco:v:90:y:2017:i:c:p:28-49.

G. Heutel. How should environmental policy respond to business cycles? Optimal policy under persistent productivity shocks. *Review of Economic Dynamics*, 15(2):244–264, 2012. URL https://EconPapers.repec.org/RePEc:red:issued:10-62.

I. Jaccard. Asset returns and labor supply in a production economy. *Journal of Money, Credit and Banking*, 46(5):889–919, 2014. ISSN 00222879, 15384616. URL http://www.jstor.org/stable/42920154.

U. J. Jermann. Asset pricing in production economies. *Journal of Monetary Economics*, 41(2):257–275, 1998. URL https://EconPapers.repec.org/RePEc:eee:moneco:v:76:y:2015:i:c:p:87-106.

O. Jordà, K. Knoll, D. Kuvshinov, M. Schularick, and A. M. Taylor. The Rate of Return on Everything, 1870–2015. *The Quarterly Journal of Economics*, 134(3):1225–1298, 2019. URL https://ideas.repec.org/a/oup/qjecon/v134y2019i3p1225-1298..html.

R. Kollmann. Tractable likelihood-based estimation of non-linear DSGE models. *Economics Letters*, 161:90–92, 2017. URL https://EconPapers.repec.org/RePEc:eee:ecolet:v:161:y:2017:i:c:p:90-92.

J. Lucas, Robert E. Macroeconomic priorities. *American Economic Review*, 93(1):1–14, March 2003. doi: 10.1257/000282803321455133. URL https://www.aeaweb.org/articles?id=10.1257/000282803321455133.

R. Mehra and E. C. Prescott. The equity premium: A puzzle. *Journal of Monetary Economics*, 15(2):145–161, March 1985. URL https://ideas.repec.org/a/eee/moneco/v15y1985i2p145-161.html.

R. G. Newell, A. B. Jaffe, and R. N. Stavins. The induced innovation hypothesis and energy-saving technological change. *Quarterly Journal of Economics*, 114(3):941–975, 1999. URL https://EconPapers.repec.org/RePEc:oup:qjecon:v:114:y:1999:i:3:p:941-975.

W. Nordhaus. *A Question of Balance: Weighing the Options on Global Warming Policies*. Yale University Press, 2008. ISBN 9780300137484. URL http://www.jstor.org/stable/j.ctt1npzkh.

W. D. Nordhaus. To slow or not to slow: the economics of the greenhouse effect. *Economic Journal*, 101(407):920–937, 1991. URL https://EconPapers.repec.org/RePEc:ecj:econjl:v:101:y:1991:i:407:p:920-37.

W. D. Nordhaus. Revisiting the social cost of carbon. *Proceedings of the National Academy of Sciences*, 114(7):1518–1523, 2017. URL https://www.pnas.org/doi/10.1073/pnas.1609244114.

L. Pàstor, R. F. Stambaugh, and L. Taylor. Dissecting Green Returns. CEPR Discussion Papers 16260, C.E.P.R. Discussion Papers, June 2021. URL https://ideas.repec.org/p/cpr/ceprdp/16260.html.

M. Piazzesi, M. Schneider, and S. Tuzel. Housing, consumption and asset pricing. *Journal of Financial Economics*, 83(3):531–569, March 2007. URL https://ideas.repec.org/a/eee/jfinec/v83y2007i3p531-569.html.

F. Smets and R. Wouters. Shocks and frictions in US business cycles: A bayesian DSGE approach. *American Economic Review*, 97(3):586–606, 2007. URL https://EconPapers.repec.org/RePEc:ecb:ecbwps:2007722.

N. L. Stokey. Are there limits to growth? *International Economic Review*, pages 1–31, 1998. URL https://EconPapers.repec.org/RePEc:ier:iecrev:v:39:y:1998:i:1:p:1-31.

T. D. Tallarini. Risk-sensitive real business cycles. *Journal of Monetary Economics*, 45(3):507–532, June 2000. URL https://ideas.repec.org/a/eee/moneco/v45y2000i3p507-532.html.

J. H. van Binsbergen, J. Fernández-Villaverde, R. S. Koijen, and J. Rubio-Ramírez. The term structure of interest rates in a DSGE model with recursive preferences. *Journal* *of Monetary Economics*, 59(7):634–648, 2012. doi: 10.1016/j.jmoneco.2012.09. URL https://ideas.repec.org/a/eee/moneco/v59y2012i7p634-648.html.

T. S. Van Den Bremer and F. Van Der Ploeg. The risk-adjusted carbon price. *American Economic Review*, 111(9):2782–2810, September 2021. doi: 10.1257/aer.20180517. URL https://www.aeaweb.org/articles?id=10.1257/aer.20180517.

R. Van Der Ploeg. Macro-financial implications of climate change and the carbon transition. mimeo, ECB Forum on Central Banking, 2020. URL https://www.ecb.europa.eu/pub/conferences/shared/pdf/20201111_ECB_Forum/academic_paper_vanderPloeg.pdf.

R. Van Der Ploeg, C. Hambel, and H. Kraft. Asset Pricing and Decarbonization: Diversification versus Climate Action. Economics Series Working Papers 901, University of Oxford, Department of Economics, Feb. 2020. URL https://EconPapers.repec.org/RePEc:oxf:wpaper:901.

P. Weil. The equity premium puzzle and the risk-free rate puzzle. *Journal of Monetary Economics*, 24(3):401–421, 1989. URL https://EconPapers.repec.org/RePEc:spo:wpmain:info:hdl:2441/8686.

P. Weil. Nonexpected utility in macroeconomics. *Quarterly Journal of Economics*, 105(1):29–42, 1990. URL https://EconPapers.repec.org/RePEc:hal:journl:hal-03393362.

M. L. Weitzman. Prices vs. quantities. *Review of Economic Studies*, 41(4):477–491, 1974. URL https://EconPapers.repec.org/RePEc:oup:restud:v:41:y:1974:i:4:p:477-491.

O. D. Zerbib. The effect of pro-environmental preferences on bond prices: Evidence from green bonds. *Journal of Banking & Finance*, 98:39–60, 2019. URL https://EconPapers.repec.org/RePEc:eee:jbfina:v:98:y:2019:i:c:p:39-60.

Appendix A: Tables

Variable	Name	Values	Sources
$\bar{N}$	Labor supply	0.20	Jaccard (2014)
δ	Depreciation rate of capital	0.025	Jermann (1998)
$\bar{g}/\bar{y}$	Public spending share in output	0.20	Christiano et al. (2014)
α	Capital intensity	0.30	Nordhaus (2017)
$\bar{e}$	U.S. carbon emissions (gigatons)	1.35	U.S. Energy Information Adm.
e^*	RoW emissions (matching $\bar{x} = 900$)	1.95	Authors calculations
$\bar{y}$	U.S. quarterly output (2015 trillions USD)	4.55	FRED
$[4(1-\gamma^X\eta)]^{-1}$	Half-life of CO_2 in years	70	Nordhaus (1991)
θ_1	Abatement cost	0.05607	Heutel (2012)
θ_2	Curvature abatement cost	2.6	Nordhaus (2017)

Table 5: Calibrated parameter values (quarterly basis)

		Prior distributions			Posterior distributions
		Shape	Mean	Std.	Mean *[0.050;0.950]*
Shock processes					
Std. productivity	σ_A	$\mathcal{IG}_1$	0.01	1	0.011 *[0.010;0.012]*
Std. spending	σ_G	$\mathcal{IG}_1$	0.01	1	0.029 *[0.028;0.031]*
Std. abatement	σ_X	$\mathcal{IG}_1$	0.01	1	0.020 *[0.019;0.022]*
Std. preference	σ_B	$\mathcal{IG}_1$	0.01	1	0.002 *[0.001;0.002]*
Std. investment	σ_I	$\mathcal{IG}_1$	0.01	1	0.025 *[0.023;0.028]*
AR(1) productivity	ρ_A	$\mathcal{B}$	0.50	0.20	0.998 *[0.997;0.999]*
AR(1) spending	ρ_G	$\mathcal{B}$	0.50	0.20	0.999 *[0.999;0.999]*
AR(1) abatement	ρ_X	$\mathcal{B}$	0.50	0.20	0.879 *[0.818;0.935]*
AR(1) preferences	ρ_B	$\mathcal{B}$	0.50	0.20	0.651 *[0.585;0.708]*
AR(1) investment	ρ_I	$\mathcal{B}$	0.50	0.20	0.976 *[0.971;0.981]*
Structural parameters					
Productivity growth rate	$\left(\gamma^Y - 1\right) \times 100$	$\mathcal{G}$	0.50	0.1	0.546 *[0.482;0.616]*
Output-CO_2 decoupling	$\left(1 - \gamma^E\right) \times 100$	$\mathcal{G}$	0.50	0.1	0.536 *[0.478;0.577]*
Discount rate	$(\beta^{-1} - 1) \times 100$	$\mathcal{N}$	0.5	0.25	1.282 *[1.031;1.545]*
Internal habits	m	$\mathcal{B}$	0.50	0.15	0.978 *[0.976;0.981]*
Tobin's Q elasticity	ϵ	$\mathcal{N}$	4	1.5	7.151 *[5.931;8.640]*
Output-CO_2 elasticity	φ_2	$\mathcal{B}$	0.50	0.20	0.159 *[0.053;0.314]*
Log-marginal data density					3027.413

Notes: $\mathcal{B}$ denotes the Beta, $\mathcal{IG}_1$ the Inverse Gamma (type 1), $\mathcal{N}$ the Normal, and $\mathcal{U}$ the uniform distribution.

Table 6: Prior and Posterior distributions of structural parameters

	Conditional on one shock				
	Productivity σ^A	Emissions σ^X	Investment σ^I	Spending σ^G	Preferences σ^B
With habits					
$400E\left(r^B_{t+1} - r^F_t\right)$	1.86	0	0.52	0.62	0.04
No habits ($m = 1$)					
$400E\left(r^B_{t+1} - r^F_t\right)$	0.01	0	0.01	0	0

Table 7: Bond premium conditional on one source of exogenous disturbance under slow-moving ($m = 0.97$) and no habits ($m = 1$).

	Tax response τ_t to TFP shock ϵ^A_t					
Horizon	Habits $m = 0.98$			No habits $m = 1$		
(quarters)	c_t	x_t	SDF_t	c_t	x_t	SDF_t
1	28.0 %	1.7 %	70.3 %	94.0 %	1.3 %	4.7 %
50	45.8 %	4.1 %	50.1 %	91.8 %	2.3 %	5.9 %

Table 8: Decomposition of carbon tax following a TFP shock into percentage contributions of consumption, carbon stock and risk free rate

	Separable utility			
	Laissez-faire	Optimal policy		
	Estimation 1972-2019	$\theta_1 = 0.056$	$\theta_1 = 0.288$	$\theta_1 = 3.500$
	(1)	(2)	(3)	(4)
$400E\left(r_t^F\right)$	7.2473	7.2541	7.2509	7.2501
$400E\left(r_{t+1}^B - r_t^F\right)$	0.0161	0.0149	0.0149	0.0150
$std(\hat{\lambda}_t)$	0.4042	0.3866	0.3959	0.3977
$E(\tau_t)$	0.0000	-	-	-
$std(\tau_t)$	0.0000	-	-	-

Notes: The first column shows the results in the laissez-faire (counter-factual) equilibrium, where we use the estimated values obtained for non-separable utility with habits. We set $m = 1$ in order to simulate the separable utility case. Column (2) is the equilibrium under an environmental tax with θ_1 set as in the literature. Columns (3) and (4) are equilibria under alternative values of θ_1 that match abatement shares of $\bar{\mu}$ of 20% and 5%.

Table 9: Counter factual robustness check – The case of separable utility (i.e., no habits).

Appendix B: Figures

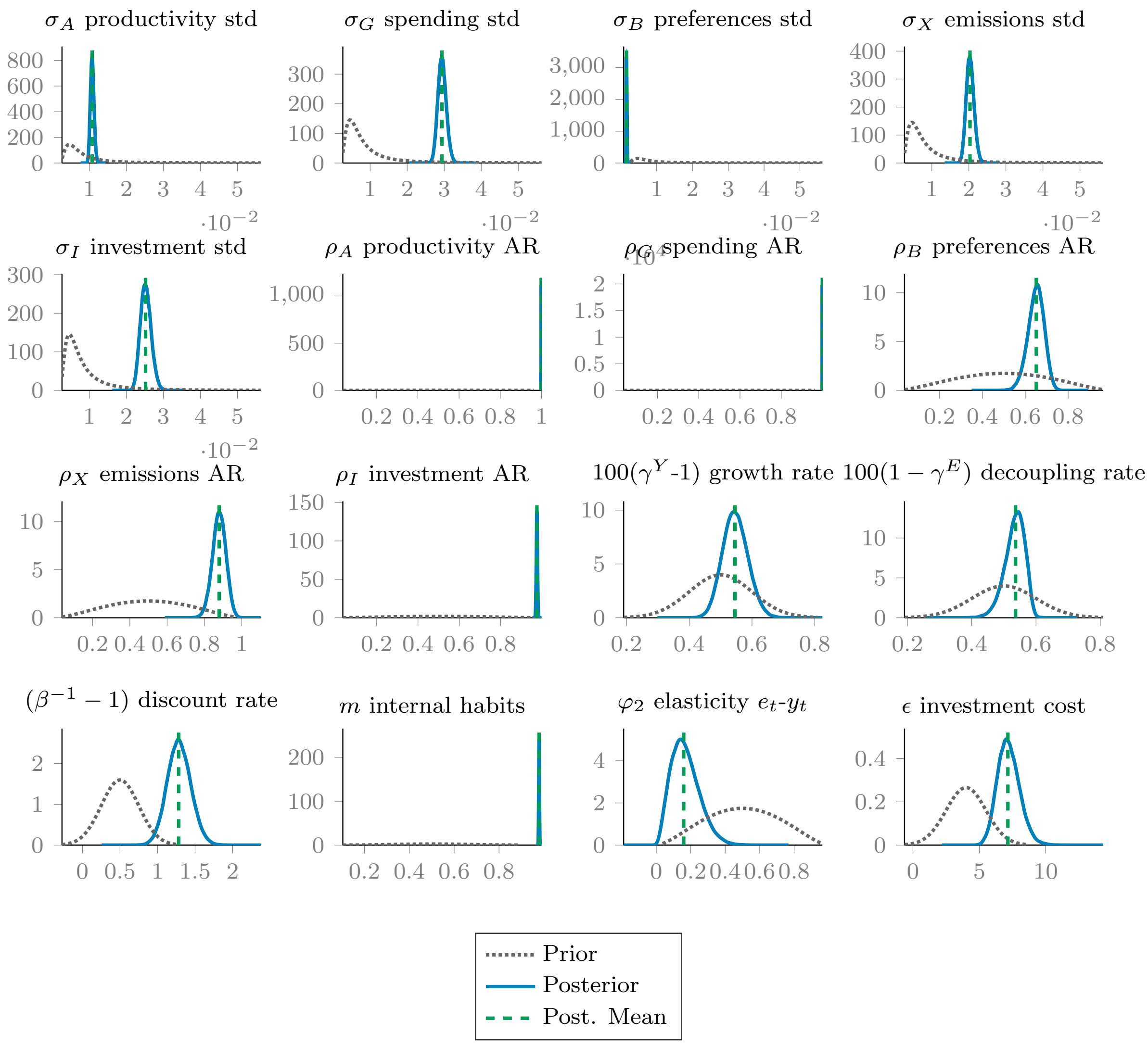
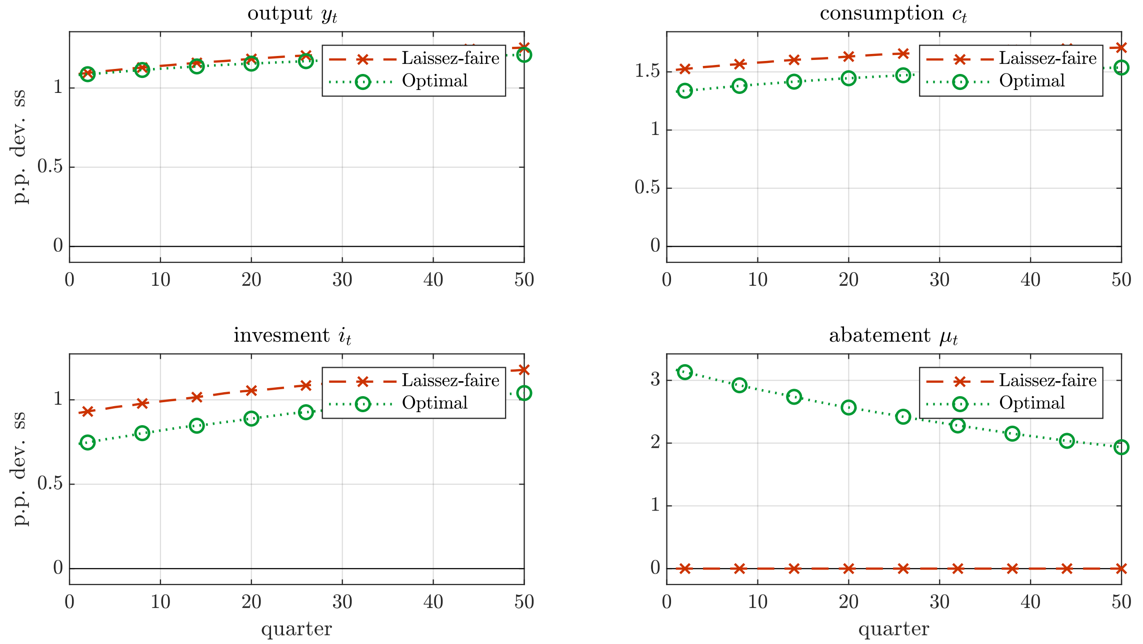
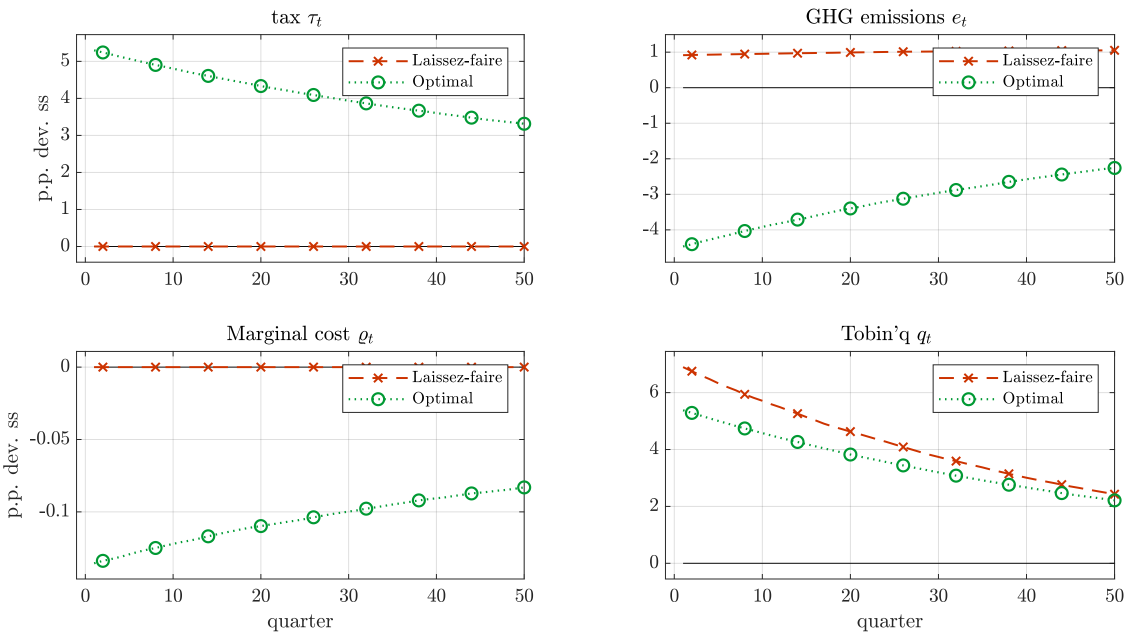


Figure 2: Prior and posterior distributions of the estimated parameters



Notes: The IRFs are generated using a second-order approximation to the policy function and are expressed as percentage deviations from the deterministic steady state. Estimated parameters are taken at their posterior mean.

Figure 3: Impulse responses from an estimated TFP shock



Notes: The IRFs are generated using a second-order approximation to the policy function and are expressed as percentage deviations from the deterministic steady state. Estimated parameters are taken at their posterior mean.

Figure 4: Impulse responses from an estimated TFP shock

Online Appendix

(not for publication)

A Balanced growth

Labor-augmenting technological progress is denoted by Γ_t. The growth rate of Γ_t determines the growth rate of the economy along the balanced growth path. This growth rate is denoted by γ^Y, where:

$$\Gamma_{t+1} = \gamma^Y \Gamma_t \tag{A.1}$$

Stationary variables are denoted by small caps, whereas variables that are growing are denoted by capital letters. For example, in the growing economy output is denoted by Y_t. De-trended output is thus obtained by dividing output in the growing economy by the level of labor-augmenting technological progress:

$$y_t = \frac{Y_t}{\Gamma_t} \tag{A.2}$$

The production function of emissions is also subject to technological progress. We denote the level of Green technological progress by Ψ_t. The growth rate of Green technological progress is γ^E.

$$\Psi_{t+1} = \gamma^E \Psi_t \tag{A.3}$$

Note that an improvement in the Green technology implies a value for γ^E that is below one.

A.1 The de-trended economy

In the growing economy, with labor-augmenting technological progress, the production function is as follows:

$$Y_t = \varepsilon_t^A A K_t^\alpha (\Gamma_t n_t)^{1-\alpha} \tag{A.4}$$

where hours worked n_t, TFP A and the technology shock ε_t^A are stationary variables.

In the de-trended economy, we have that:

$$y_t = \varepsilon_t^A A k_t^\alpha {n_t}^{1-\alpha} \tag{A.5}$$

Moreover, the economy's resource constraint is:

$$y_t = c_t + i_t + f(\mu_t) y_t \tag{A.6}$$

where the share of abated emissions μ_t is a stationary variable that takes values between 0 and 1. The capital-accumulation equation in the growing economy is:

$$K_{t+1} = (1-\delta)K_t + I_t \tag{A.7}$$

In the de-trended economy, we thus have that:

$$\gamma^Y k_{t+1} = (1-\delta)k_t + i_t \tag{A.8}$$

Emissions, which we denote by E_t, in the growing economy are given as follows:

$$E_t = (1-\mu_t)\varphi_1 Y_t^{1-\varphi_2} \Psi_t \tag{A.9}$$

where φ_1 and φ_2 are parameters. In the de-trended economy, we have that:

$$e_t = (1-\mu_t)\varphi_1 y_t^{1-\varphi_2} \tag{A.10}$$

where:

$$e_t = \frac{E_t}{\Psi_t \left(\Gamma_t\right)^{1-\varphi_2}} \tag{A.11}$$

In the growing economy, the stock of emissions in the atmosphere is denoted by X_t. The accumulation of emissions in turn depends on the level of new emissions E_t :

$$X_{t+1} = \eta X_t + E_t + E_t^* \tag{A.12}$$

where η is the fraction of the stock of emissions that remains in the atmosphere and E_t^* is the flow of emissions from the rest of the world. To obtain a balanced growth path, we assume that emissions in the rest of the world grow at a constant rate that is the same as in the United States:

$$e^* = \frac{E_t^*}{\Psi_t \left(\Gamma_t\right)^{1-\varphi_2}}$$

In the de-trended economy, we therefore have that:

$$\gamma^X x_{t+1} = \eta x_t + e_t + e^* \tag{A.13}$$

where, to simplify notation, we define γ^X as follows:

$$\gamma^X = \gamma^E \left(\gamma^Y\right)^{1-\varphi_2}. \tag{A.14}$$

In the growing economy, the utility function is given as follows:

$$\sum_{t=0}^{\infty} \beta^t \frac{\left(\frac{C_t}{\Theta_t X_t} - H_t\right)^{1-\sigma}}{1-\sigma} \tag{A.15}$$

where C_t is consumption, X_t the stock of emissions, H_t the habit stock, β the subjective discount factor, σ the curvature parameter, and Θ_t a variable that grows at a constant rate in the steady state.

The de-trended utility function takes the following form:

$$\sum_{t=0}^{\infty} \beta^t \frac{(\Gamma_0 \left(\gamma^Y\right)^t)^{1-\sigma} \left(\frac{c_t}{\phi x_t} - h_t\right)^{1-\sigma}}{1-\sigma} \tag{A.16}$$

where Γ_0 denotes labor augmenting technological progress at time 0 and where:

$$C_t = \Gamma_t c_t \text{ and } H_t = \Gamma_t h_t$$

A stationary utility function is therefore obtained by assuming that the trend variable Θ_t grows at a deterministic rate in the steady state where:

$$\Theta_t = \frac{\phi}{\Psi_t \left(\Gamma_t\right)^{1-\varphi_2}} \tag{A.17}$$

This variable can be interpreted as the awareness of households to the effect of climate change. In the main text, to limit the number of degrees of freedom, we normalize the climate awareness coefficient ϕ as well as the initial value of labor augmenting technological progress Γ_0 to 1.

B The optimal tax

B.1 Centralized problem

We characterize here the first-best equilibrium. A social planner maximizes welfare, which leads producers to internalize the social cost of emissions. The problem for the social planner reads as follows:

$$
\begin{aligned}
\mathcal{L} = E_0 & \left\{ \sum_{t=0}^{\infty} \beta^t \log\left(\varepsilon_t^B \frac{c_t}{x_t} - h_t\right) \right. \\
& + \sum_{t=0}^{\infty} \beta^t \lambda_t \left[y_t - c_t - i_t - g_t - f\left(\mu_t\right) y_t \right] \\
& + \sum_{t=0}^{\infty} \beta^t \lambda_t q_t \left[(1-\delta) k_t + \left[\frac{\chi_1}{1-\epsilon} \left(\varepsilon_t^I \frac{i_t}{k_t} \right)^{1-\epsilon} + \chi_2 \right] k_t - \gamma^Y k_{t+1} \right] \\
& + \sum_{t=0}^{\infty} \beta^t \lambda_t \varrho_t \left[\varepsilon_t^A A k_t^{\alpha} n_t^{1-\alpha} - y_t \right] + \sum_{t=0}^{\infty} \beta^t \xi_t \left[\gamma^Y h_{t+1} - m h_t - (1-m) \varepsilon_t^B \frac{c_t}{x_t} \right] \\
& + \sum_{t=0}^{\infty} \beta^t \lambda_t \upsilon_{Xt} \left[\gamma^X x_{t+1} - \eta x_t - e_t - e^* \right] \\
& \left. + \sum_{t=0}^{\infty} \beta^t \lambda_t \upsilon_{Et} \left[e_t - \left(1-\mu_t\right) \varepsilon_t^X \varphi_1 y_t^{1-\varphi_2} \right] \right\}
\end{aligned}
$$

The marginal utility of consumption c_t is:

$$\left(\varepsilon_t^B \frac{c_t}{x_t} - h_t\right)^{-1} \frac{1}{x_t} \varepsilon_t^B = \lambda_t + \xi_t (1-m) \frac{1}{x_t} \varepsilon_t^B \tag{B.1}$$

Optimal investment i_t is given by:

$$1 = \varepsilon_t^I q_t \chi_1 \left(\varepsilon_t^I \frac{i_t}{k_t} \right)^{-\epsilon} \tag{B.2}$$

The optimal capital supply is given by:

$$q_t = \beta^Y E_t \frac{\lambda_{t+1}}{\lambda_t} \left\{ q_{t+1} \left((1-\delta_K) + \frac{\chi_1}{1-\epsilon} \left(\varepsilon_{t+1}^I \frac{i_{t+1}}{k_{t+1}} \right)^{1-\epsilon} + \chi_2 - \chi_1 \left(\varepsilon_{t+1}^I \frac{i_{t+1}}{k_{t+1}} \right)^{1-\epsilon} \right) + \varrho_{t+1} \alpha \frac{y_{t+1}}{k_{t+1}} \right\}$$

where:

$$\beta^Y = \beta/\gamma^Y$$

The optimality condition with respect to the habit stock:

$$\xi_t - m\beta^Y E_t\xi_{t+1} - \beta^Y E_t \left(\varepsilon^B_{t+1} \frac{c_{t+1}}{x_{t+1}} - h_{t+1} \right)^{-1} = 0 \tag{B.3}$$

The first-order condition on output y_t is:

$$[1 - f(\mu_t)] - \varrho_t - v_{Et}(1 - \varphi_2)\frac{e_t}{y_t} = 0$$

The optimal fraction of abatement μ_t is given by:

$$f'(\mu_t)\, y_t = v_{Et}\frac{e_t}{(1 - \mu_t)} \tag{B.4}$$

The optimal quantity of emissions e_t per quarter reads as follows:

$$v_{Et} = v_{Xt} \tag{B.5}$$

While the shadow value of pollution is:

$$\lambda_t v_{Xt} = \beta^X E_t \lambda_{t+1} \left(\eta v_{Xt+1} + \frac{c_{t+1}}{x_{t+1}} \right) \tag{B.6}$$

where:

$$\beta^X = \beta/\gamma^X \tag{B.7}$$

B.2 Laissez-faire equilibrium

Assume the following functional form for $f(\mu_t)$:

$$f(\mu_t) = \theta_1 \mu_t^{\theta_2} \tag{B.8}$$

Firms are profit-maximizing:

$$\max_{k_t, n_t, \mu_t, e_t} d_t = y_t - w_t n_t - i_t - \theta_1 \mu_t^{\theta_2} y_t - \tau_t e_t$$

Subject to the capital-accumulation constraint:

$$\gamma^Y k_{t+1} = (1-\delta)k_t + \left(\frac{\chi_1}{1-\epsilon}\left(\varepsilon_{It}\frac{i_t}{k_t}\right)^{1-\epsilon} + \chi_2\right)k_t \tag{B.9}$$

Subject to the emission law of motion:

$$e_t = \varepsilon_{Xt}(1-\mu_t)\varphi_1 y_t^{1-\varphi_2} \tag{B.10}$$

And subject to the supply curve:

$$y_t = \varepsilon_{At}k_t^{\alpha}n^{1-\alpha} \tag{B.11}$$

The Lagrangian reads as follows:

$$\mathcal{L} = E_0\sum_{t=0}^{\infty}\beta^t\frac{\lambda_t}{\lambda_0}\left\{\begin{array}{c} y_t - w_t n - i_t - \theta_1\mu_t^{\theta_2}y_t - \tau_t e_t \\ +v_{Et}\left[e_t - \varepsilon_{Xt}(1-\mu_t)\varphi_1 y_t^{1-\varphi_2}\right] \\ +\varrho_t\left[\varepsilon_{At}Ak_t^{\alpha}n^{1-\alpha} - y_t\right] \\ +q_t\left[(1-\delta)k_t + \left(\frac{\chi_1}{1-\epsilon}\left(\varepsilon_{It}\frac{i_t}{k_t}\right)^{1-\epsilon} + \chi_2\right)k_t - \gamma^Y k_{t+1}\right] \end{array}\right\}$$

The first-order condition on emissions e_t is given by:

$$v_{Et} = \tau_t \tag{B.12}$$

Optimal minimization of labor inputs N_t reads as:

$$w_t = \varrho_t(1-\alpha)\frac{y_t}{n_t} \tag{B.13}$$

The optimal quantity of physical capital k_{t+1}:

$$\lambda_t q_t = \beta^Y E_t\lambda_{t+1}q_{t+1}\left[(1-\delta) + \frac{\chi_1}{1-\epsilon}\left(\varepsilon_{It+1}\frac{i_{t+1}}{k_{t+1}}\right)^{1-\epsilon} + \chi_2 - \chi_1\left(\varepsilon_{It+1}\frac{i_{t+1}}{k_{t+1}}\right)^{1-\epsilon}\right] + \beta^Y E_t\lambda_{t+1}\alpha\frac{y_{t+1}}{k_{t+1}}\varrho_{t+1} \tag{B.14}$$

The marginal profit for an additional unit produced is:

$$\varrho_t = 1 - \theta_1 \mu_t^{\theta_2} - v_{Et}(1-\varphi_2)\frac{e_t}{y_t} \tag{B.15}$$

Optimal abatement μ_t is given by:

$$v_{Et}\frac{e_t}{1-\mu_t} = \theta_1\theta_2\mu_t^{\theta_2 - 1} y_t \tag{B.16}$$

In the *laissez-faire* economy, there is no environmental policy:

$$\tau_t = 0$$

Recall that firms do not consider the stock of emissions x_t as a state variable. In equilibrium the cost of carbon v_{Xt}, as considered by firms, is 0 because they do not internalize the effects of emissions on households. As a result, since in the *laissez-faire* equilibrium τ_t is set to 0, the first-order conditions with respect to emissions imply that $v_{Et} = 0$. From the first-order conditions with respect to μ_t and y_t, this in turn implies $\mu_t = 0$ and $\varrho_t = 1$.

B.3 Competitive equilibrium under optimal policy

The first-best equilibrium that corresponds to the problem of the social planner can be attained by setting the tax τ_t equal to the price of carbon. In the centralized equilibrium, the price of carbon is determined by the optimality condition with respect to x_t. The optimal tax is therefore:

$$\tau_t = v_{Xt} \tag{B.17}$$

Once the optimal tax is implemented, in the *laissez-faire* equilibrium, equation (B.12) then implies that:

$$v_{Et} = v_{Xt} \tag{B.18}$$

The optimality condition shown in equation (B.5) is therefore satisfied, as the cost of abating emissions is exactly equal to the social cost of emissions.

C Robustness over climate dynamics with carbon cycle models

C.1 Climate dynamics à la Cai and Lontzek (2019)

The three box climate dynamics is modeled following Cai and Lontzek (2019) specification. First, the carbon emissions stock X_t law of motion reads:

$$\gamma_X x_{t+1} = \Phi_x x_t + b_1 e_t \tag{C.1}$$

with $x_t = (x_t^{AT}, x_t^{UO}, x_t^{LO})^T$ the three-dimensional vector describing the masses of carbon concentrations in the atmosphere, and upper and lower levels of the ocean. Emissions e_t are the total current flow of carbon dioxide in the atmosphere with $b_1 = (1, 0, 0)^T$. The matrix $\Phi_x = (\Phi_x^1, \Phi_x^2, \Phi_x^3)$ summarizes the relationship between the actual stocks of emissions and the pre-industrial equilibrium states of the carbon cycle system, where $\Phi_x^1 = (\phi_{11}, \phi_{21}, \phi_{31})^T$, $\Phi_x^2 = (\phi_{12}, \phi_{22}, \phi_{32})^T$, and $\Phi_x^3 = (\phi_{13}, \phi_{23}, \phi_{33})^T$.

For completeness (although in our framework temperature does not alter the marginal utility of consumers directly, but rather via the stock of emissions x_t^{AT}), we define the relationship (as seen in the DICE model) between the temperature vector t_t^o (i.e. both the atmosphere and ocean temperatures) and the stock of emissions in the atmosphere x_t^{AT} as following:

$$\gamma_X t_{t+1}^o = \Phi_t t_t^o + b_2 \mathrm{RF}(x_t^{AT}) \tag{C.2}$$

with temperature vector $t_t^o = (t_t^{oAT}, t_t^{oOC})^T$ and the matrix $\Phi_T = (\phi_1^T, \phi_2^T)^T$, which represents the heat diffusion process between ocean and air. $b_2 = (\xi_T, 0)^T$ with ξ_T the climate sensitivity parameter. Furthermore, atmospheric temperature is affected by radiative forcing, $\mathrm{RF}(.)$, which is the interaction between radiation and atmospheric CO_2 as following:

$$\mathrm{RF}(x_t^{AT}) = \tilde{\eta_F} \log_2 \left(\frac{x_t^{AT}}{\bar{x}^{AT}} \right) + \mathrm{RF}_t^{Exo} \tag{C.3}$$

where $\tilde{\eta_F} = \log(\Psi_t)\eta_F$ represents the Radiative forcing parameter, which is subject to a corrective trend $\log(\Psi_t)$ allowing for a BGP. [21] RF_t^{Exo} represents the exogenous radiative

[21] We calibrate $\tilde{\eta_F}$ such that we retrieve a temperature of 1^oC with respect to the pre-industrial level at the steady state.

forcing dynamic and reads as:

$$\mathrm{RF}_t^{Exo} = \begin{cases} -0.06 + 0.0036t, & \text{for t} < 100 \\ 0.3 \text{ otherwise} \end{cases} \tag{C.4}$$

C.2 Climate dynamics à la Dietz and Venmans (2019)

As shown in the main paper emissions and firms section, the emission stock is modeled using one reservoir. We, however, we chose η (i.e. the decay rate) to be sufficiently high (close to one) to allow for convergence. This is without a loss of generality as the focus of our paper is on the business cycle implications:

$$\gamma^X x_{t+1} = \eta x_t + e_t + e^* \tag{C.5}$$

In addition, similarly to the case of the three box climate dynamics following Cai and Lontzek (2019), for completeness, global temperature t_t^o is linearly proportional to the level of the emission stock, which in turn is proportional to cumulative emissions:

$$\gamma^X t_t^o = \upsilon_1^o(\upsilon_2^o x_{t-1} - t_{t-1}^o) + t_{t-1}^o, \tag{C.6}$$

with υ_1^o and υ_2^o chosen following Dietz and Venmans (2019).

C.2.1 Calibration

All parameters calibrations are taken from Cai and Lontzek (2019) and Dietz and Venmans (2019).

C.2.2 Simulation results

In this section, we present a robustness exercise. We match the 2020 level of atmospheric temperature of 1.0-1.1^{o}C as well as the stock of emissions of about 900GtCO. We show that under the *laissez-faire* scenario, and with a carbon cycle climate model with three carbon reservoirs, the bond premium level is consistent with our baseline model estimation where we rely on the non-linear inversion filter and a one reservoir carbon layer in the spirit of Dietz and Venmans (2019). The results are also consistent with the particle filter estimations. The following table summarizes the result:

Model counterpart	Name	Values
ϕ_{11}	Emission stock decay parameter	0.87
ϕ_{12}	Emission stock decay parameter	0.1960
ϕ_{13}	Emission stock decay parameter	0.00
ϕ_{21}	Emission stock decay parameter	0.12
ϕ_{22}	Emission stock decay parameter	0.7970
ϕ_{23}	Emission stock decay parameter	0.0015
ϕ_{31}	Emission stock decay parameter	0.0
ϕ_{32}	Emission stock decay parameter	0.0070
ϕ_{33}	Emission stock decay parameter	0.9985
ϕ_1^T	Temperature parameter	1/0.1005
ϕ_2^T	Temperature parameter	0.08/0.025
ξ_T	Temperature parameter	3.1
η_F	Radiative forcing parameter	3.6813
$\tilde{\eta_F}$	Radiative forcing parameter	1.61
$\bar{x}^{AT}$	Pre-industrial level of emission stock	588
υ_1^o	Temperature dynamics parameter	0.5
υ_2^o	Temperature dynamics parameter	0.00125

Table 10: Calibrated parameter values

Variable	Three reservoir climate model	One reservoir climate model
$E(c_t)$	2.5953	2.5952
$E(x_t^{AT})$	937.2336	933.5076
$E(t^{oAT})$	1.01	1.1
$E(r^F)$	4.2728	4.2599
$400E\left(r_{t+1}^B - r_t^F\right)$	3.0098	3.0357

Notes: The first column shows the simulation results (with all our five estimated shocks) in the laissez-faire equilibrium, where we use the three reservoir emissions stock climate framework following Cai and Lontzek (2019), while the second column display the results in the case of one reservoir following Dietz and Venmans (2019).

Table 11: Laissez-faire simulation results under different climate modeling frameworks

D Asset pricing implications of the environmental externality

With a non-separable specification, the environmental externality affects agents' marginal utility of consumption. Climate policies can have asset pricing implications because of their effect on the level as well as the dynamics of the stock of emissions x. In our setup, an important concept is therefore the elasticity of marginal utility to a change in the stock of emissions. With our specification of internal habit formation, marginal utility of consumption is given as follows:

$$\lambda_t = \left(\varepsilon_t^B \frac{c_t}{x_t} - h_t\right)^{-1} \varepsilon_t^B \frac{1}{x_t} - \xi_t (1-m) \varepsilon_t^B \frac{1}{x_t}, \tag{D.1}$$

where ξ_t is the Lagrange multiplier on the law of accumulation of the habit stock in Equation 9. The dynamics of the Lagrange multiplier is determined by the following Euler condition:

$$\xi_t = m\beta^Y E_t \xi_{t+1} + \beta^Y E_t \left(\varepsilon_{t+1}^B \frac{c_{t+1}}{x_{t+1}} - h_{t+1}\right)^{-1}, \tag{D.2}$$

A partial equilibrium elasticity, which measures the sensitivity of marginal utility to a change in x while keeping everything else constant can be defined as follows:

$$\Upsilon_t^{\lambda,x} = \frac{\partial \lambda_t / \partial x_t}{\lambda_t} x_t$$

This partial equilibrium concept can be interpreted as a measure of short-term elasticity. It measures the effect of a change in the stock of emissions on marginal utility before agents take into account the effect of future expected values of consumption and the externality. Indeed, with this internal specification, marginal utility depends on both current and future values of c and x through the Lagrange multiplier ξ.

Since agents choose optimal trajectories for c, x, and h, for plausible parameter values, this elasticity is always positive. Consequently, everything else equal, an increase in the stock of emissions raises agents' marginal utility of consumption. It is important to note that the habit parameter m, where $0 \leq m \leq 1$, has a crucial impact on this elasticity. This can be illustrated by evaluating this elasticity in the deterministic steady state of the model. In this case, a closed-form expression can be obtained and is given as follows:

$$\Upsilon^{\lambda,x} = \left(\frac{\frac{1-m}{\gamma^Y - m}}{1 - \frac{1-m}{\gamma^Y - m}} + \frac{\beta^Y(1-m)}{1-m\beta^Y} \right) \left(1 - \frac{\beta^Y(1-m)}{1-m\beta^Y} \right)^{-1}$$

Without habits, which in our setup corresponds to the case $m = 1$, this elasticity is therefore equal to zero.[22] For values of m smaller than 1, however, this elasticity is positive as the externality affects the short-term dynamics of marginal utility. Indeed, a lower value of m increases this elasticity and therefore the importance of the environmental externality for marginal utility and hence asset prices. Given the importance of this parameter for our results, we will estimate it using data on consumption and emissions.

[22] This is due to the log utility specification that we use. In the more general case, this short-term elasticity depends on the curvature coefficient and can be positive when m is set to 1.

E The response to other shocks

The response to a preference shock is shown in Figure 5. As shown by the upper and lower left panels, preference shocks only have a very small effect on the dynamics of consumption and emissions under *laissez-faire*. These shocks also have a negligible impact on the risk-free rate and the risk premium. In contrast, and as shown in the upper-right panel, these shocks play a more interesting role once the optimal policy is introduced. Indeed, a preference shock that reduces agents' marginal utility of consumption is an opportunity to compensate for this decline in aggregate demand by raising expenditures on abatement. This effect in turn explains the decline in emissions documented in the lower-left panel of Figure 5.

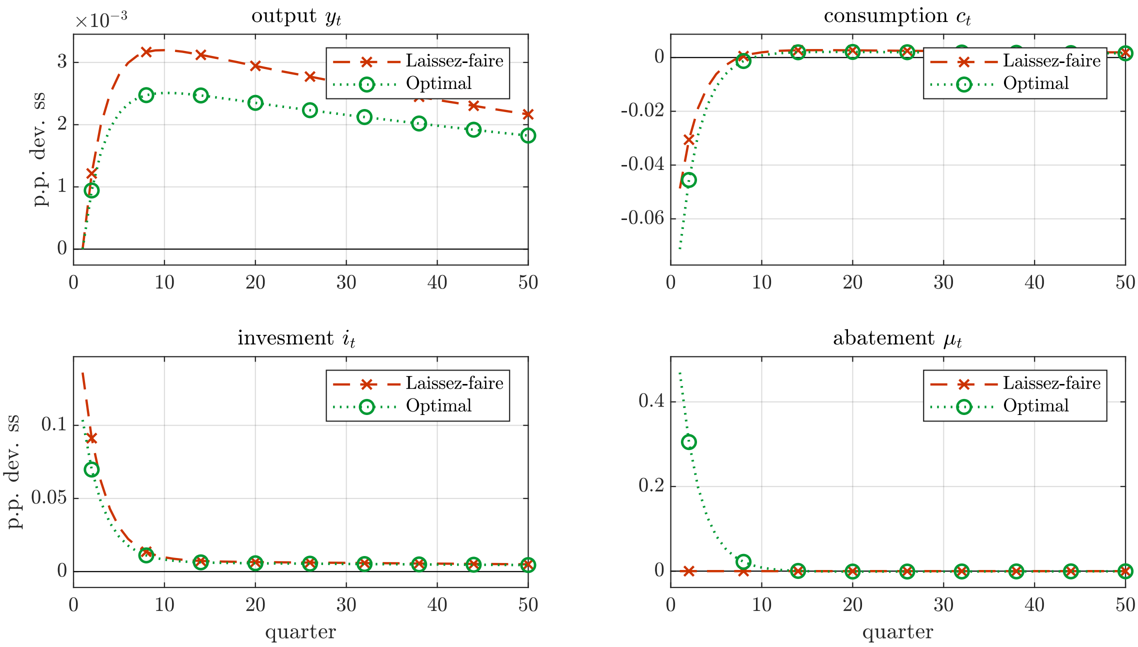


Figure 5: Impulse responses from a preference shock

The response to a government spending shock is shown in Figure 6. In both cases, a positive government-spending shock reduces consumption. In our model, this can first be explained by the negative wealth effect from the shock. On impact, the shock has no effect on production, but increases the share of output allocated to government spending. On impact, consumption and investment therefore have to fall.

This negative wealth effect is reinforced by a negative substitution effect. As in models with habits and adjustment costs, this reflects the increase in the real interest

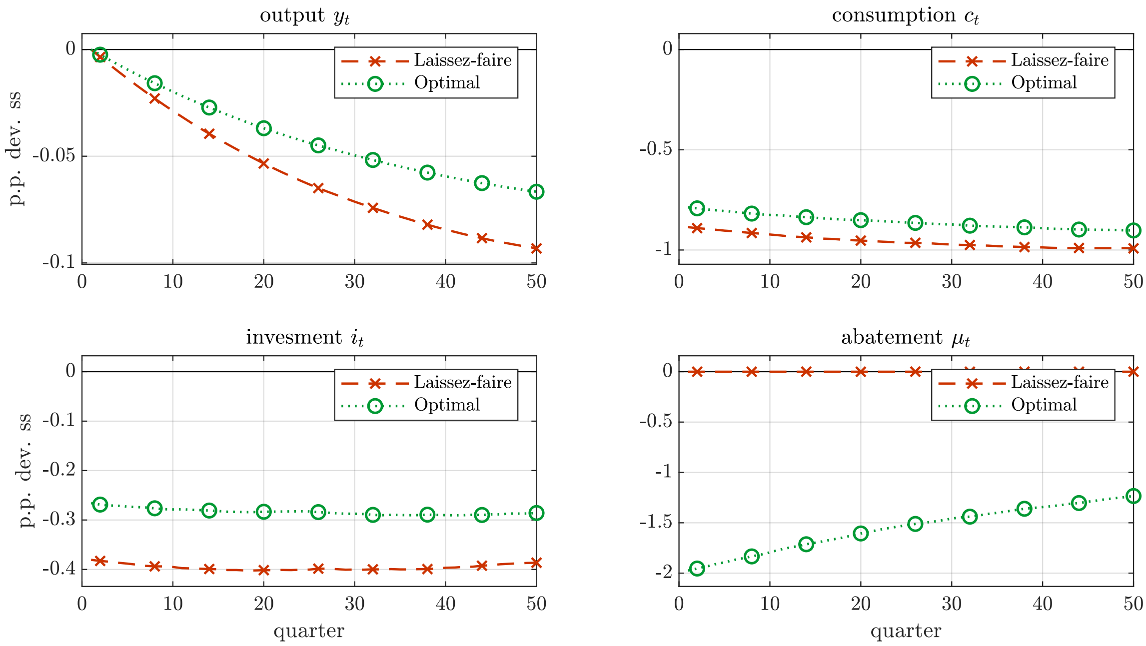


Figure 6: Impulse responses from a government-spending shock

rate generated by the shock. As agents become more reluctant to save as consumption falls, the real interest rate has to rise to restore equilibrium.

This illustrates the trade-off between environmental protection and macroeconomic stabilization in this model. Whereas emissions decline in the *laissez-faire* case, the social planner chooses to increase the stock of pollution. The social planner internalizes that the shock reduces the resources available for consumption. It is therefore optimal to mitigate the effect of the shock by lowering abatement as well as the tax (see the upper-right and lower-right panels of Figure 6). When the consumption cost is too large, environmental policy is used to mitigate the adverse effect of the shock. In this case, the planner chooses macroeconomic stabilization over environmental protection.

Relative to a standard business-cycle model, the main innovation is the introduction of emission shocks. In the *laissez-faire* equilibrium, consumption falls on impact and then increases above its steady-state level (see the upper-left panel of Figure 7). As emission shocks do not affect output, their main effect is to reduce agents' utility. The only way to mitigate the effect of this rise in the emissions stock is then to increase consumption. The problem is that to do so income has to rise first. The only way of raising income in this model is to accumulate capital. This explains why on impact consumption needs to fall. This fall is necessary to finance an increase in investment, which in turn allows agents to increase output. A few quarters after the shock, as the higher investment raises output, consumption gradually increases. The short-term decline in consumption is therefore compensated by a rise in the medium-term. As illustrated by the red-crossed line in the upper-left panel of Figure 7, consumption initially declines and then increases above its steady state a few periods after the shock.

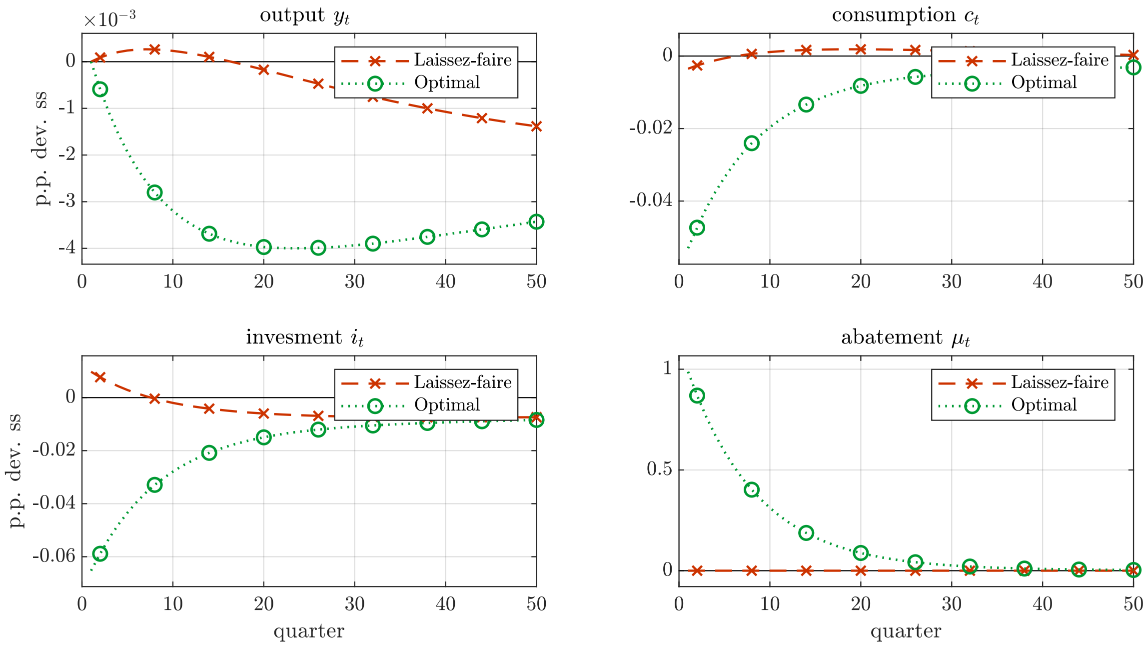


Figure 7: Impulse responses from an emissions shock

As can be seen by comparing the red-crossed and green-circled line, the response of consumption and emissions is very different under the optimal policy. The planner chooses to allocate a large fraction of resources to the abatement technology. It is therefore optimal to reduce consumption and investment to finance abatement to prevent emissions from rising.

As illustrated in the lower-right panel, the social planner also chooses to reduce the tax. The tax reduction helps to mitigate the fall in consumption and investment that is necessary to finance abatement.

The response to an investment-specific technology shock is shown in Figure 8. This shock generates a negative co-movement between consumption and investment. Relative to the *laissez-faire* equilibrium, the optimal policy attenuates the rise in consumption induced by the shock. This lower increase in consumption can be explained by the fall in emissions that occurs under the optimal policy. As in the case of a technology shock, it is no longer necessary to compensate the increase in emissions by raising consumption when

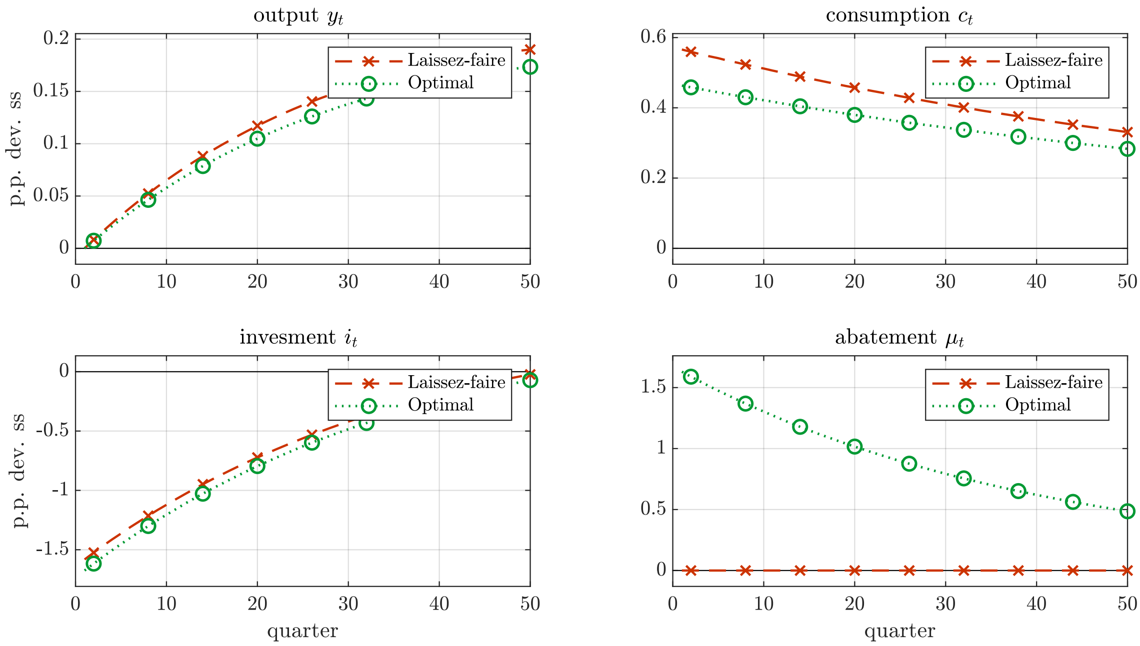


Figure 8: Impulse responses from an investment-specific technological shock

the tax is implemented. As a result, the increase in consumption can be smaller during booms, which in turn reduces the volatility of consumption over the business cycle.

F Comparison with the particle filter

In this section, we investigate whether our results continue to hold with alternative filtering methods other than the inversion filter. In the asset-pricing literature, the natural benchmark for non-linear models is particle filtering, as the latter allows likelihood-based inference of nonlinear and/or non-normal macroeconomic models (e.g. van Binsbergen, Fernández-Villaverde, Koijen, and Rubio-Ramírez, 2012; Andreasen, 2012). The inversion and particle filters are algorithms that recursively update and estimate the state and find the innovations driving a stochastic process, given a set of observations.

The inversion filter does so by inverting the model's recursion rule, while the particle filter uses a sequential Monte Carlo method. Both estimation methods require the use of numerical approximation techniques that introduce error between the "true" value of the parameter and its estimate.

In the implementation of the particle filter, it is common to posit that the data-generating process (DGP) includes measurement errors. As underlined by Cuba-Borda et al. (2019), the presence of measurement error may seem to be an innocuous way of getting around degeneracy issues when choosing a computationally-manageable number of particles. As the number of innovations must be the same as the number of observable variables, the inversion filter may exhibit misspecification errors if measurement errors are part of the DGP. It is nonetheless standard to assume no measurement errors for linearized models, following Smets and Wouters (2007).

	Historical Data		Artificial Data
	(1) Particle	(2) Inversion	(3) Inversion
Estimated Parameters			
Productivity AR(1)	0.9808 *[0.9745;0.9859]*	0.9884	0.9800
Productivity std	0.0157 *[0.0154;0.0159]*	0.0156	0.0152
Risk Premia			
Premium laissez-faire	6.5300 *[5.2906;8.2404]*	6.0794	6.9247
Premium tax policy	4.1015 *[3.3545;5.1266]*	3.8491	4.3384

Notes: 25,000 iterations of the random-walk Metropolis-Hastings algorithm are drawn for the posterior uncertainty for each model. The maximization of the mode is carried out via simplex optimization routines. The confidence intervals in column(1) are drawn from the posterior uncertainty from 1,000 draws from the Metropolis-Hastings algorithm. The artificial data in column (1) are obtained from 1,000 simulations of the estimated model with the particle-filtering method.

Table 12: Outcomes from the particle vs. inversion filters under historical and simulated data

To gauge how much our results are robust to misspecification errors, we estimate our model solved up to the second order with innovations to productivity estimated with output growth as an observable variable. We limit ourselves to productivity shocks as these are the main driver of the risk premium. The rest of the parameters are set to the posterior mean taken from the previous estimation in Table 6. We consider three situations: (1) the particle filter algorithm as described in Fernández-Villaverde and Rubio-Ramírez (2007) estimated on US data;[23] (2) the inversion filter estimated on US data; and (3) the inversion filter estimated on 1,000 simulated output-growth data from the particle filter from column (1) that includes measurements error. The latter allows us to see whether measurement errors affect the inference of structural parameters when using the inversion filter. Table 5 shows the results.

The comparison of columns (1) and (2) shows whether the inversion filter and particle filter outcomes differ. The two filters provide a very similar measure of the likelihood function, as the differences in the inference of structural parameters are only minor. In particular, the outcome from the inversion filter always lies in the confidence interval of that from the particle filter, both for the estimated structural parameters and the premium effects. The fact that the lower risk premium from environmental policy is very similar across estimation methods is also reassuring, and suggests that our results may remain similar under alternative filtering methods.

To make sure that the robustness of our results to measurement errors holds unconditionally in larger samples, we follow Fernández-Villaverde and Rubio-Ramírez (2005) and simulate 1,000 output-growth data from the model in column (1). We estimate the model on this artificial data using the inversion filter and list the outcomes in column (3). The inversion filter infers a value that is close to the true parameter values, despite the presence of measurement errors.

[23] We use 10,000 particles to approximate the likelihood, and set the variance of the measurement errors to 10% of the sample variance of the observables to help estimation. These values are very standard in the literature.

G Replication file

A dynare replication file for the simplest version of the model can be accessed by using the following link:

https://www.dropbox.com/s/owglekfxll4d2lc/code_package.zip?dl=1

The software dynare can be downloaded online:

https://www.dynare.org/

Policy Interaction and the Transition To Clean Technology

Ghassane Benmir*† Josselin Roman†

March 2022

Abstract

We study the implication of setting a market for carbon permits to meet the net-zero objective for the Euro Area. Using a dynamic stochastic general equilibrium model with financial frictions and an environmental externality embedded in a two-sector (green and brown) production economy, we identify two inefficiencies arising from the European Emissions Trading System: i) a welfare wedge and ii) a risk premium distortion. We find that macroprudential climate risk-weights on loans aimed at ensuring financial stability during the transition can also help to close the welfare wedge. Then, we show that quantitative easing rules would allow authorities to offset the effect of carbon price volatility on corporate risk premia. In addition, central banks have an incentive to tilt large-scale asset purchase programs toward green bonds when the macroprudential authority simultaneously implements climate risk-weights.

Keywords: Climate Change, Macroprudential Policy, Green QE, Welfare, Risk Premium.

JEL: Q54, Q58, E32, E52.

*Corresponding author. London School of Economics and Political Science; , London WC2A 2AE, UK; email: g.benmir@lse.ac.uk

†PSL Research University – Université Paris Dauphine, 75016 Paris, France.

The authors are extremely grateful to Valentina Bosetti, Anna Creti, Wouter den Haan, Simon Dietz, Roger Fouquet, Garth Heutel, Ivan Jaccard, Tierra McMahon, Jean-Guillaume Sahuc, Katheline Schubert, Luca Taschini, Rick Van der Ploeg, Aude Pommeret, Christian Traeger, Gauthier Vermandel, Bertrand Villeneuve, and participants from Paris-Dauphine Economics workshop, LSE seminar, the ASSA, CEBRA, MIT GCFP, and EAERE annual meetings, as well as the Climate Risk Workshop of the FRBSF for useful discussions and for providing comments on an earlier draft. All errors and omissions are our own. The usual disclaimer applies. The authors are also grateful for funding and support for this research from the LSE - Grantham Research Institute, the ESRC through the Centre for Climate Change Economics and Policy, and PSL Research University - Paris Dauphine.

1 Introduction

Climate change has shifted from a fringe issue to a worldwide emergency. Our understanding of the phenomenon and our willingness to act have developed significantly, in part paralleling the ways in which climate change is being experienced around the globe. It has become a hot topic where academics, industry, and lay people alike are finding common ground. As such, growing academic awareness is leading to important literature in the domain. The implementation of a strategy for the substantial reduction of greenhouse gases (GHG) at the global level has become a major priority. Since the Rio Conference in 1992, a debate has raged in academic and political circles over the growth-environmental trade-off. Discussions focus on the means by which economic activities could align with environmental concerns instead of being hindered by assumed mutual exclusivity. In practice, especially in the short and medium terms, however, financial and economic activity on one side, and environmental policy on the other, are in tension. A need for both medium/long and short-term policies aimed at bridging the gap between environmental sustainability and economic efficiency, as well as addressing financial stability, are in dire need, in order to foster economic transition. Of special concern are climate actions that may strongly impact macroeconomic activity, given the potentially high added cost of GHG offsetting. With the substantial effects of climate actions on the overall economy, a growing body of research from the field of macroeconomics and macro-finance, among others, are now tackling these issues.

In this paper, we study the implication of setting a market for carbon permits to meet the net-zero target (in the European Union (EU), this corresponds to an emission reduction objective of 55 percent by 2030 compared to the 1990 level). To de-carbonize the economy, the price of carbon is expected to rise sharply, as the welfare maximizing optimal policy is shown to not be sufficient (Golosov et al. [2014] and Hassler et al. [2020]). This could potentially lead to both welfare distortions in the long run and financial disruptions in the short run (depending on the market structure and price volatility). A framework seeking a better integration of macro-finance and environment would allow, on one hand, for a better understanding of carbon mitigation pricing policies as well as their impacts on different macro aggregates including consumer welfare, which is shown to be significantly impacted and differs depending on the carbon pricing policy market design in place (Sager [2019]). On the other hand, this framework would also allow for investigating the linkages and impacts of the climate externality on financial aggregates such as the natural rate of interest and the risk premium (Benmir et al. [2020] and Bauer and Rudebusch [2021]). In our quantitative analysis, we take the EU net-zero policy as given and investigate how macro-financial policies could interact with it.

This paper is tightly linked to three strands of literature that address macro-environmental issues and the role of macro-financial authorities.

The first strand focuses on long-term analysis of the nexus between climate policies and the macroeconomy and can be traced back to the early work of Nordhaus [1991]. A wide range of literature of integrated assessment models (IAMs) extended the framework developed by Nordhaus to account for uncertainty in climate dynamics and damages (see Stern [2008], Weitzman [2012], and Dietz and Stern [2015], among others). Golosov et al. [2014] use a dynamic stochastic general equilibrium (DSGE) model to show that the optimal carbon price is not impacted by future uncertainty. They also find that following the optimal policy would not allow for global warming to be kept well below 2°C over a 50 years horizon. This is consistent with our simulations, which show that the price of carbon needs to rise well above its optimal counterpart to set the Euro Area (EA) on the net-zero path. While Golosov et al. [2014] compute transition pathways resulting from the implementation of an optimal carbon price policy, we instead consider the carbon price resulting from the European Trading System (ETS) cap policy. In the same spirit of our work, Hassler et al. [2020] investigate several sub-optimal policy scenarios using a multi-country IAM. These scenarios, however, are not designed to represent current carbon policies in the European Union (EU) and IAMs do not feature a role for the financial system. In a recent paper, Van der Ploeg et al. [2020] study the financial consequences of climate risk with respect to portfolio choices. Although our article shares similar components with the latter, we differ by explicitly modeling financial intermediaries. Carattini et al. [2021] and Diluiso et al. [2021] also build environmental DSGE (E-DSGE) models with financial frictions, yet they do not account for trend growth and uncertainty around the level of TFP and carbon price in their long-term simulations, both of which are featured in our analysis. Furthermore, they both simulate transition pathways as a response to exogenous shocks, rather than using deterministic simulations. However, similar to Carattini et al. [2021], we consider macroprudential policy as a long-term tool that can be used to shape banks' balance sheets in order to contain climate risk rather than a short-term tool to address financial shocks (Diluiso et al. [2021]). With respect to the literature on long-term transition pathways, our simulations feature both deterministic trends and uncertainty on the level of TFP, as well as on the carbon price. While Cai and Lontzek [2019] also perform long-term transitions with uncertainty around the trend of TFP and climate damages, we focus on TFP and the price of carbon as we consider a shorter horizon. In addition, we use a Newton-based method to compute the solution where Cai and Lontzek [2019] use value function iteration.

We also provide a dynamic analysis of welfare, which allows us to study the benefits of macroprudential policy along the transition to the net-zero target.

The second strand of literature relevant to our work focuses on business cycle implications of environmental policies. Angelopoulos et al. [2010], Fischer and Springborn [2011], Heutel [2012], among others,[1] paved the way for business cycle analysis under an environmental externality. The main focus of these papers is to assess the efficiency of different environmental policies. In recent months, papers such as Diluiso et al. [2021] or Carattini et al. [2021] incorporated a financial sector in order to study the role of monetary and macroprudential policies in the fight against climate change. Our short-term analysis is tangentially related to these two papers. In our framework, however, the monetary authority intervenes to correct a distortion in risk premia stemming from carbon price volatility, which we estimate based on observed ETS futures price data. The role of the central bank thus arises endogenously from the transmission of carbon price shocks to financial variables through the marginal cost of firms, while Diluiso et al. [2021] explore the benefits of both monetary and macroprudential policies in response to an exogenous shock to the quality of brown assets.

Finally, this paper is also linked to a strand of literature assessing central banks' large-scale asset purchases (LSAP) programs, and especially the so-called green quantitative easing (green QE). In the wake of the Great Financial Crisis, Gertler and Karadi [2011] provided a framework to study the impact of central banks' LSAP programs in response to a shock to the quality of capital. With respect to green QE, Ferrari and Nispi Landi [2021] investigate the impact of a series of positive unexpected shocks to the central bank's holdings of green bonds to simulate an assets purchase program. We differ by considering that LSAP programs are expected by agents, as central banks communicate about them beforehand. We also consider two types of green LSAP programs (transitory and permanent) and the interaction between them and pre-announced macroprudential policy.

Our modeling device borrows components from several macroeconomic types of models. We first build on the canonical versions of New Keynesian (NK) models such as Woodford [2003], Smets and Wouters [2003] or Christiano et al. [2005] to derive the core of our economy.[2] Second, we add environmental components as in Nordhaus [2008], Heutel [2012], and Dietz and Venmans [2019], which allow for the analysis of the dynamics of the economy under the presence of the CO_2 externality. However, as opposed to Heutel [2012], we differentiate between green and brown firms instead of using one sole representation for firms, thus bor-

[1] E.g. Bosetti et al. [2014], Annicchiarico and Di Dio [2015], and Dissou and Karnizova [2016]. For an extensive literature review distinguishing between the long-term and business cycle environmental macroeconomics, respectively, please refer to Schubert [2018].

[2] Note that for simplicity we abstract from wages rigidities and labor disutility.

rowing from the multi-sector literature (Carvalho and Nechio [2016] among others[3]). Finally, we include balance sheet constrained financial intermediaries as in Gertler and Karadi [2011]. Given that we introduce a macroprudential authority that can alter this constraint, we also draw on Pietrunti [2017].

As we will consider monetary policy, we only focus on the EA. We perform medium/long-term simulations both for transition pathways to meet the net-zero target and for LSAP programs along the transition to net-zero. As for business cycle simulations, we rely on second order impulse responses to analyze the impact of the ETS carbon price shock on macro-financial aggregates. The novelty of our approach is that our transition pathways feature both long-run deterministic growth rates (i.e. labor augmenting technology and carbon cap policy) and stochastic components around these trends. This allows us to compute confidence intervals for our variables of interest using Monte-Carlo simulations. Furthermore, we rely on the simulated method of moments (SMM) to estimate key structural parameters and match the EA macroeconomic, financial, and environmental empirical data.

Our main theoretical result highlights the inefficiencies stemming from the EU ETS design. In the long term we show that, as the cap policy diverges from the optimal social cost of carbon (SCC), the loss on welfare increases, whereas, in the short term the ETS market design induces volatility in the carbon price that distorts risk premia.

On applied grounds, our contribution is to propose tools to mitigate these inefficiencies. Using numerical simulations, we find that an instrument that deviates from the optimal policy (SCC), such as the ETS, is needed to meet the net-zero target. However, this induces a substantial cost in terms of welfare (3 percent consumption equivalent). To ease the welfare burden, we show that a sectoral risk-weight (*i.e.* climate risk-weight) macroprudential policy is able to reduce the wedge gap, without imposing infeasible regulatory weights on assets held by financial intermediaries and jeopardizing financial stability. In particular, a sectoral macroprudential policy favorable to the green sector boosts green capital and output, inducing a gain in welfare, compared to the sub-optimal policy economy without macroprudential policy, as the green sector is less sensitive to the rise in carbon price. With respect to the distortion on risk premia, we show that short-term monetary policy instruments (*i.e* QE rules) are able to restore the equilibrium in the financial markets. Thus, macroprudential and monetary policies could play an important role in offsetting the negative effects stemming from the implementation of a market for carbon permits. Finally,

[3] We note that a substantial literature referred to as "directed technical progress" uses two sectors (green and dirty) to investigate the transition to a green economy and impacts of different environmental policies. See, for example, Smulders and De Nooij [2003], Grimaud and Rouge [2008], Di Maria and Valente [2008], Acemoglu et al. [2012], Aghion et al. [2016], Acemoglu et al. [2019].

we investigate the role of asset purchase programs over the net-zero transition and find that central banks would have an incentive to tilt their portfolio of assets toward the green sector when macroprudential policy takes into account climate risk. More generally, we show that QE rules could be used as a short-term countercyclical tool, while sectoral macroprudential policy could play a more structural role, allowing for a smooth transition toward net-zero emissions.

Our actual findings could be further reinforced if we were to see an increase in the share of the green sector, as illustrated in our simulated transition in figure 2 and figure 3, and as argued in the work of Acemoglu et al. [2016], where the focus is on the long-term transition strategies.

This paper is organized as follows: section 2 presents the model, section 3 explains the solution method, section 4 discusses the results, and section 5 concludes.

2 The Model

Using the NK-DSGE framework as a foundation, the present paper investigates the potential role of fiscal policy, central bank unconventional monetary policy, and macroprudential policy, in mitigating climate change impacts on macroeconomic and financial aggregates. We first model our two-sector economy following Carvalho and Nechio [2016]. Then, we incorporate the environmental component following Nordhaus [2008], Heutel [2012], and Dietz and Venmans [2019], among others. Finally, we model financial intermediaries drawing on Gertler and Karadi [2011].

In a nutshell, the economy modeled is described using a discrete set up with time $t \in (0, 1, 2, \ldots \infty)$. The production sectors produce two goods (final and intermediate goods) using labor and capital. Households consume, offer labor services, and rent out capital to firms via financial intermediaries. Public authorities decide on the fiscal and environmental policy, the central bank decides on the monetary policy, and the financial authority sets the macroprudential policy.

2.1 The Household

At each period, the representative household supplies labor inelastically to the two sectors of our economy (i.e green and brown sectors denoted by $k \in \{g, b\}$[4]), while they also consume and save. Households can either lend their money to the government or to financial

[4]Where ‘g’ refers to the green sector and ‘b’ to the brown sector.

intermediaries, who will in turn leverage and finance firms. In each household there are bankers and workers. Each banker manages a financial intermediary and transfers profits to the household. Nevertheless, households cannot lend their money to a financial intermediary owned by one of their members. Household members who are workers supply labor and return their salaries to the household to which they belong.

Agents can switch between the two occupations over time. There is a fraction f of agents who are bankers and a probability θ_B that a banker remains a banker in the next period. Thus, $(1-f)\theta_B$ bankers become workers every period and vice versa, which keeps the relative proportions constant. Exiting bankers give their retained earnings to households, which will use them as start-up funds for new bankers.

Households solve the following maximization problem:

$$\max_{\{C_t, B_{t+1}\}} E_t \sum_{i=0}^{\infty} \beta^i \left[\frac{(C_{t+i} - hC_{t+i-1})^{1-\sigma}}{1-\sigma} \right] \tag{1}$$

s.t.

$$C_t + B_{t+1} = \sum_k g(\varkappa) \left(W_{t,k} L_{t,k} + \Pi_{t,k} \right) + \Pi_t^T + T_t + R_t B_t, \tag{2}$$

where $\beta \in (0,1)$ is the discount factor and σ shapes the utility function of the representative household associated with risk consumption C_t. The consumption index C_t is subject to external habits with degree $h \in [0;1)$. Labor supply $L_{t,k}$[5] in each sector is remunerated at nominal wage $W_{t,k}$. Note that the sector share for the green g is $g(\varkappa) = \varkappa$ and $(1-\varkappa)$ for the brown sector b. $\Pi_{t,k}$ are profits from the ownership of firms, while Π_t^T are profits from the ownership of financial intermediaries and capital producing firms. T_t is lump sum taxes. As we assume that intermediaries deposits and government bonds are one period bonds, $R_t B_t$ is interest received on bonds held and B_{t+1} is bonds acquired.

Solving the first order conditions and denoting ϱ_t as the marginal utility of consumption, the consumption/saving equations are:

$$\varrho_t = (C_t - hC_{t-1})^{-\sigma} - \beta h E_t \left\{ (C_{t+1} - hC_t)^{-\sigma} \right\}, \tag{3}$$

$$1 = \beta E_t \Lambda_{t,t+1} R_{t+1}, \tag{4}$$

with $\Lambda_{t-1,t} = \frac{\varrho_t}{\varrho_{t-1}}$ the expected variation in the marginal utility of consumption.

[5]We note that inelastic labor $L_{t,k} = \bar{L_k}$, where $\bar{L_k}$ is the steady state level of labor in each sector.

2.2 The Firms

2.2.1 The Final Firms

Using the multi-sector framework from Carvalho and Nechio [2016], and under non-perfect competition, we assume that production comprises two sectors. Our representative final firms produce a final good $Y_{t,k}$ in these two competitive sectors. Using no more than capital and labor to produce the intermediate good Y_{jt} (where $j \in (0,1)$ is the continuum of intermediate goods firms), intermediate firms supply the final sectors. In other words, the "bundling" of intermediate goods within the two sectors leads to a final good. The final economy good is a constant elasticity of substitution aggregate of the two sectors:

$$Y_t = \left(\varkappa^{\frac{1}{\theta}} Y_{t,g}^{1-\frac{1}{\theta}} + (1-\varkappa)^{\frac{1}{\theta}} Y_{t,b}^{1-\frac{1}{\theta}} \right)^{\frac{1}{1-\frac{1}{\theta}}}, \tag{5}$$

with $\theta \in (1, \infty)$ the elasticity of substitution between the two sectors, and $\varkappa$ the weight of each sector. The final firms in the model are looking for profit maximization (in nominal terms), at a given price P_t subject to the intermediate goods j in each of the two sectors k at prices $P_{jt,k}$:

$$\max_{Y_{jt}} \Pi_t^{\text{Final}} = P_t Y_t - \varkappa \int_0^1 P_{jt,g} Y_{jt,g} dj - (1-\varkappa) \int_0^1 P_{jt,b} Y_{jt,b} dj, \tag{6}$$

where the aggregation of green and brown firms reads as:

$$Y_{t,k} = \int_0^1 \left(Y_{jt,k}^{1-\frac{1}{\theta_k}} \right)^{\frac{1}{1-\frac{1}{\theta_k}}}. \tag{7}$$

However, while we assume a constant elasticity of substitution between the final sectors, we consider a different elasticity of substitution θ_k between differentiated intermediate goods within each sector. As the goods of the two sectors entail different costs, a different elasticity of substitution is considered. This assumption, which shapes the marginal cost structure, is based both on theoretical work of Tucker [2010] as well as on the empirical findings of Chan et al. [2013] and Chegut et al. [2019], where it is found that green projects entail higher marginal cost (7-13 percent higher costs for green projects in the construction industry compared to non green projects depending on the 'greenness' of the project, and 5-7 percent higher costs in the cement and iron & steel sectors, respectively).

The first order condition for the final firm profit maximization problem yields:

$$Y_{jt,k} = \left(\frac{P_{jt,k}}{P_{t,k}}\right)^{-\theta_k} \left(\frac{P_{t,k}}{P_t}\right)^{-\theta} Y_t. \tag{8}$$

Under perfect competition and free entry, the price of the final good is denoted P_t, while the price $P_{t,k}$ is the price index of sector-k intermediate goods. Finally, the price $P_{jt,k}$ is the price charged by firm j from sector k.

Prices of final aggregate goods and for each sector are given by:

$$P_t = \left(\varkappa P_{t,g}^{1-\theta} + (1-\varkappa) P_{t,b}^{1-\theta}\right)^{\frac{1}{1-\theta}}, \tag{9}$$

$$P_{t,k} = \left(\int_0^1 P_{jt,k}^{1-\theta_k} dj\right)^{\frac{1}{1-\theta_k}}. \tag{10}$$

2.2.2 The Intermediate Firms

Our economy is composed of two categories of firms: i) green firms, which are environmentally-friendly and ii) brown firms with a higher emission intensity. The representative firms j in each sector k of the modeled economy uses capital $K_{t,k}$ and labor $L_{t,k}$ to produce the intermediate good. In our framework, firms' productivity is subject to climate dynamics. As presented in Golosov et al. [2014] real business cycle model, the environmental externality constrains the Cobb-Douglas production function of the firms, where the negative externality deteriorates the environment and alters production possibilities for firms. However, we differ from Golosov et al. [2014] by incorporating damages from the stock of emissions through the level of temperature as follows:

$$Y_{jt,k} = \varepsilon_t^{A_k} d(T_t^o) K_{jt,k}^{\alpha} (\Gamma_t L_{jt,k})^{1-\alpha},\ \alpha \in (0,1), \tag{11}$$

where Γ_t is the economy growth trend and $d(T_t^o)$ a convex function relating the temperature level to a deterioration in output ($d(T_t^o) = ae^{-\frac{b}{\Gamma_t{}^2} T_t^{o2}}$), with $(a,b) \in \mathbb{R}^2$, which is borrowed from Nordhaus and Moffat [2017]. As highlighted by Benhabib et al. [1991], Jaimovich and Rebelo [2009], and Queralto [2020], the business cycle literature typically features preferences and/or production functions with $\Gamma_t = 1$ for all t. Within a business cycle framework, we usually assume no long-run growth. However, as we are also interested in the transition pathways, our economy features a growth trend Γ_t different than 1 in hours worked. Therefore, we introduce ${\Gamma_t}^2$ to the damage sensitivity parameter b, such that $d(T_t^o) = ae^{-\frac{b}{\Gamma_t^2} T_t^{o2}}$.

The goal is to ensure the existence of a balanced growth path without a loss of generality, as over the studied period $d(T_t^o) = ae^{-\frac{b}{\Gamma_t^2}T_t^{o2}} \approx ae^{-bT_t^{o2}}$. In addition, the growth rate of Γ_t, which determines the growth rate of economy, is set exogenously to γ^Y where $\Gamma_t = \gamma^Y \Gamma_{t-1}$. Furthermore, α is the standard elasticity of output with respect to capital, and $\varepsilon_t^{A_k}$ is a sector-specific technology shock that follows an $AR(1)$ process: $\varepsilon_t^{A_k} = \rho_{A_k}\varepsilon_{t-1}^{A_k} + \sigma_{A_k}\eta_t^{A_k}$, with $\eta_t^{A_k} \sim \mathcal{N}(0,1)$.

Global temperature T_t^o is linearly proportional to the level of the emission stock, which in turn is proportional to cumulative emissions as argued by Dietz and Venmans [2019]:[6,7]

$$T_t^o = \upsilon_1^o(\upsilon_2^o X_{t-1} - T_{t-1}^o) + T_{t-1}^o, \tag{12}$$

with υ_1^o and υ_2^o chosen following Dietz and Venmans [2019].

Furthermore, the carbon emissions stock X_t follows a law of motion:

$$X_t = (1-\gamma_d)X_{t-1} + E_t + E_t^*, \tag{13}$$

where $E_t = \sum_k g(\varkappa)\int_0^1 E_{jt,k}dj$ is the aggregate flow of emissions from both the green and brown firms at time t and γ_d is the decay rate. $E_t^* = E^*\Gamma_t$ represents the rest of the world emissions and is used to pin down the actual steady state level of the stock of emission in the atmosphere. We assume that the rest of the world's emissions grow at the same rate as the domestic GDP over the period studied.

The emissions level is shaped by a non-linear abatement technology $\mu_{jt,k}$ that allows firms to reduce their emissions inflows:

$$E_{jt,k} = (1-\mu_{jt,k})\varphi_k Y_{jt,k}. \tag{14}$$

Emissions $E_{jt,k}$ at firm level are proportional to the production $Y_{jt,k}$ with φ_k the fraction of emissions to output in each sector.[8] Also, emissions could be reduced at the firm level through an abatement effort $\mu_{jt,k}$. The firms are allowed to invest in an abatement technology, but

[6] To allow for convergence in the auto-regressive law of motion for the stock of emissions process (shown in equation (13)) we slightly depart from the transient climate response to cumulative carbon emissions theory and set $\gamma_d \neq 0$. However, we choose γ_d sufficiently low such that $X_t \approx X_0 + \sum_{i=0}^{t}(E_i + E_i^*)$.

[7] We note that while differences on climate dynamics and damages modeling over the long horizon (whether à la Golosov et al. [2014], à la Nordhaus [2017], or à la Dietz and Venmans [2019], among others) induce consequent impacts on macroeconomic aggregate equilibriums, over the business cycle horizon (and under equivalent calibrations), these modeling specifications do not induce significant impacts on macroeconomic aggregate equilibriums.

[8] Contrary to Cai and Lontzek [2019], we consider $\varphi_{t,k} = \varphi_k$ constant overtime and calibrate it using Euro Area emissions to GDP data, as we focus on shorter time horizons (less than 50 years).

it represents an extra cost.

We model the direct abatement effort costs as follows:

$$Z_{jt,k} = f(\mu_{jt,k})Y_{jt,k}, \tag{15}$$

where

$$f(\mu_{jt,k}) = \theta_{1,k}\mu_{jt,k}^{\theta_{2,k}},\ \theta_1 > 0,\, \theta_2 > 1, \tag{16}$$

with $\theta_{1,k}$ and $\theta_{2,k}$ the cost efficiency of abatement parameters for each sector.

Thus, profits of our representative intermediate firms in each sector $\Pi_{jt,k}$ will be impacted by the presence of the environmental externality. Revenues are the value of intermediate goods $Y_{jt,k}$, while costs arise from: i) wages $W_{t,k}$ (paid to the labor force $L_{jt,k}$), ii) rents $R^K_{t,k}$ (on capital $K_{jt,k}$), iii) abatement investments $f(\mu_{jt,k})$, and iv) the cost of releasing carbon in the atmosphere $\tau_{et,k}E_{jt,k}$ (i.e. the carbon price paid to the government).

$$\begin{aligned}\Pi_{jt,k} &= \frac{P_{jt,k}}{P_t}Y_{jt,k} - W_{t,k}L_{jt,k} - R^K_{t,k}K_{jt,k} - \theta_{1,k}\mu_{jt,k}^{\theta_{2,k}}Y_{jt,k} - \tau_{et,k}E_{jt,k} \\ &= \left(\frac{P_{jt,k}}{P_t} - MC_{t,k}\right)Y_{jt,k},\end{aligned} \tag{17}$$

As firms are not free to update prices each period, they first choose inputs so as to minimize costs, given a price, subject to the demand constraint.

The cost-minimization problem yields the marginal cost, which can be expressed following the first-order conditions with respect to the firm's optimal choice of capital, labor, abatement, and production level, respectively:

$$R^K_{t,k} = \alpha\Psi_{jt,k}\frac{Y_{jt,k}}{K_{jt,k}}, \tag{18}$$

$$W^K_{t,k} = (1-\alpha)\Psi_{jt,k}\frac{Y_{jt,k}}{L_{jt,k}}, \tag{19}$$

$$\tau_{et,k} = \frac{\theta_{1,k}\theta_{2,k}}{\varphi_k}\mu_{jt,k}^{\theta_{2,k}-1}, \tag{20}$$

$$MC_{jt,k} = MC_{t,k} = \Psi_{t,k} + \theta_{1,k}\mu_{t,k}^{\theta_{2,k}} + \tau_{et,k}(1-\mu_{t,k})\varphi_k, \tag{21}$$

where $\Psi_{jt,k} = \Psi_{t,k}$[9] is the marginal cost component related to the same capital-labor ratio all firms from each sector choose. This marginal cost component is common to all intermediate firms, but differs across sectors.

[9] $\Psi_{jt,k} = \Psi_{t,k} = \frac{1}{\alpha^\alpha(1-\alpha)^{1-\alpha}}\frac{1}{\varepsilon_t^{A,k}d(T_t^o)}\left(W_{t,k}\right)^{1-\alpha}\left(R^K_{t,k}\right)^\alpha$.

Equation (20) is the optimal condition on abatement: abating CO_2 emissions is optimal when its marginal gain equals its marginal cost. This equation highlights the key role of the carbon price in shaping firms' decisions. In addition, abatement efforts $\mu_{t,k}$ are common to all firms of the same sector, as the environmental cost is also common to all firms of the same sector. Furthermore, as the impact of the environmental externality is not internalize by firms (i.e. they take X_t and T_t^o as given), the shadow value of the environmental externality is zero.

The total marginal cost captures both abatement and emissions costs as shown above in equation (21). Note that in the case of the laissez-faire scenario, $MC_{t,k} = \Psi_{t,k}$, as the firms are not subject to emissions and abatement constraints.

In addition, monopolistic firms engage in a price setting à la Rotemberg.[10] Price update is subject to an adjustment cost given by $\Delta^P_{jt,k} = \frac{\theta^P}{2}\left(\frac{P_{jt,k}}{P_{jt-1,k}} - 1\right)^2$. Thus, profit maximization subject to the demand from final firms reads as follows:

$$\max_{P_{jt,k}} \mathbb{E}_t \sum_{i=0}^{\infty} \beta^i \Lambda_{t,t+i} \left(\Pi_{jt+i,k} - \Delta^P_{jt+i,k} Y_{t+i}\right) \tag{22}$$

$$\text{s.t. } Y_{jt,k} = \left(\frac{P_{jt,k}}{P_{t,k}}\right)^{-\theta_k} \left(\frac{P_{t,k}}{P_t}\right)^{-\theta} Y_t,$$

where $\beta^i \Lambda_{t,t+i} = \beta^i \frac{\varrho_{t+i}}{\varrho_t}$ is the real stochastic discount factor, or as commonly called in the macro-finance literature, the pricing kernel.

The NK Philips Curve pricing equation for each sector is as follows:

$$\theta^P \pi_{t,k}(\pi_{t,k} - 1) = \left(\frac{P_{t,k}}{P_t}\right)^{-\theta} \left(\frac{P_{t,k}}{P_t}(1-\theta_k) + \theta_k MC_{t,k}\right) + E_t \left\{ M_{t,t+1} \frac{Y_{t+1}}{Y_t} \theta^P \pi_{t+1,k}(\pi_{t+1,k} - 1) \right\}, \tag{23}$$

with sectoral inflation $\pi_{t,k} = P_{t,k}/P_{t-1,k}$.

The aggregate inflation $\pi_t = \frac{P_t}{P_{t-1}}$ reads as:

$$\pi_t = \left(\varkappa^{\frac{1}{\theta}} \frac{P_{t-1,g}}{P_{t-1}} \pi_{t,g}^{1-\frac{1}{\theta}} + (1-\varkappa)^{\frac{1}{\theta}} \frac{P_{t-1,b}}{P_{t-1}} \pi_{t,b}^{1-\frac{1}{\theta}} \right)^{\frac{1}{1-\frac{1}{\theta}}}. \tag{24}$$

In addition, please note that the j-index referring to our intermediate firms collapses as all firms for each sector, which are capable of setting their price optimally at t, will make

[10] As a robustness exercise we set price stickiness à la Calvo (Appendix section C.3) and find similar results.

the same decisions.

2.2.3 Capital Producing Firms

We assume that households own capital producing firms and receive profits. Capital producing firms buy specific types of capital from intermediate goods firms at the end of period t, repair depreciated capital, and create new capital. They then sell both the new and re-furbished capital. The relative price of a unit of capital is $Q_{t,g}$ for green and $Q_{t,b}$ for brown. We suppose that there are flow adjustment costs associated with producing new capital as in Jermann [1998]. Accordingly, capital producing firms face the following maximization problem:

$$\max_{\{I_{t,k}\}} E_t \sum_{s=0}^{\infty} \beta^s \Lambda_{t,t+s} \left\{ (Q_{t+s,k} - 1) I_{t+s,k} - f_k(.)(I_{t+s,k}) \right\} \tag{25}$$

$$\text{with} \quad I^n_{t,k} = I_{t,k} - \delta K_{t,k}, \tag{26}$$

$$K_{t+1,k} = K_{t,k} + I^n_{t,k}, \tag{27}$$

$$\text{and} \quad f_k(.) = \frac{\eta_i}{2} \left(\frac{I_{t,k}}{I_{t-1,k}} - \theta^I \right)^2, \tag{28}$$

where $I^n_{t,k}$ and $I_{t,k}$ are net and gross capital created, respectively. $\delta K_{t,k}$ is the quantity of re-furbished capital, and η_i the inverse elasticity of net investment to the price of capital.[11] Thus, we get the following value for $Q_{t,k}$:

$$Q_{t,k} = 1 + f_k(.) + f'_k(.) \left(\frac{I_{t,k}}{I_{t-1,k}} \right) - \beta E_t \left\{ \Lambda_{t,t+1} f'_k(.) \left(\frac{I_{t+1,k}}{I_{t,k}} \right)^2 \right\}. \tag{29}$$

2.3 Financial Intermediaries

We augment the setup of Gertler and Karadi [2011] to allow financial intermediaries to invest in both green and carbon-intensive firms. We also modify the incentive constraint to provide a realistic implementation of macroprudential policy through regulatory risk-weights on loans.

A representative bank's balance sheet can be depicted as:

$$Q_{t,g} S_{t,g} + Q_{t,b} S_{t,b} = N_t + B_t, \tag{30}$$

[11] The term θ^I is set such that the over the balanced growth path ($f_k \left(\frac{i_{t,k}}{i_{t-1,k}} \right) = 0$), where $i_{t,k}$ is the de-trended net investment.

where $S_{t,g}$ and $S_{t,b}$ are financial claims on green and brown firms and $Q_{t,g}$ and $Q_{t,b}$ their respective relative price. Note that $S_{t,k} = K_{t,k}$, as firms from both sectors do not face frictions when requesting financing. On the liability side, N_t is the banks' net worth and B_t is debt to households. Over time, the banks' equity capital evolves as follows:

$$N_t = R_{t,g}Q_{t-1,g}S_{t-1,g} + R_{t,b}Q_{t-1,b}S_{t-1,b} - R_t B_{t-1}, \tag{31}$$

$$N_t = (R_{t,g} - R_t)Q_{t-1,g}S_{t-1,g} + (R_{t,b} - R_t)Q_{t-1,b}S_{t-1,b} + R_t N_{t-1}, \tag{32}$$

where $R_{t,k} = \frac{R^K_{t,k} - (Q_{t,k} - \delta)}{Q_{t-1,k}}$ denotes the gross rate of return on a unit of the bank's assets from $t-1$ to t for sector k.[12]

The goal of a financial intermediary is to maximize its equity over time. Thus, we can write the following objective function:

$$V_t = E_t \left\{ \sum_{i=1}^{\infty} (\Delta\beta)^i \Lambda_{t,t+i} (1 - \theta_B) \theta_B^{i-1} N_{t+i} \right\}, \tag{33}$$

with $(1-\theta_B)$ the exogenous probability of going out of business for a banker and Δ a parameter accounting for the subjective discount factor of bankers.[13] We introduce a regulator in charge of the supervision of financial intermediaries. Drawing on Pietrunti [2017], we assume that the regulator requires that the discounted value of the bankers' net worth should be greater than or equal to the current value of assets, weighted by their relative risk:

$$V_t \geq \lambda(\lambda_g Q_{t,g} S_{t,g} + \lambda_b Q_{t,b} S_{t,b}), \tag{34}$$

with λ the risk-weight on loans and λ_g and λ_b sectoral specific weights that can be applied to loans for green and/or brown firms. The regulator can modify these weights, altering the constraint weighing on banks and thus the allocation of loans between sectors. In our baseline version of the model, however, we consider the case where λ_g and λ_b are both equal to one, and we calibrate λ and other banks-related parameters to match the capital ratio of banks in the Euro Area as well as risk premia levels. We guess that the value function is linear of the form $V_t = \Gamma^B_t N_t$ so we can rewrite V_t as:

$$V_t = \max_{S_{t,g}, S_{t,b}} E_t \left\{ \Delta\beta \Lambda_{t,t+1} \Omega_{t+1} N_{t+1} \right\}, \tag{35}$$

[12] Note that the depreciated capital has a value of one as adjustment costs only apply to net investment.
[13] This parameter allows us to perfectly match financial steady state data for the EA.

where $\Omega_t \equiv 1 - \theta_B + \theta_B \Gamma_t^B$. Maximization subject to the regulatory constraint (34) yields the following first order and slackness conditions:

$$\Delta \beta E_t \left\{ \Lambda_{t,t+1} \Omega_{t+1} (R_{t+1,k} - R_{t+1}) \right\} = \nu_t \lambda_k \lambda, \tag{36}$$

$$\nu_t \left[\Gamma_t^B N_t - \lambda (\lambda_g Q_{t,g} S_{t,g} + \lambda_b Q_{t,b} S_{t,b}) \right] = 0, \tag{37}$$

where ν_t is the multiplier for constraint (34). One interesting result is that we get:

$$N_t \geq \Xi_t (\lambda_g Q_{t,g} S_{t,g} + \lambda_b Q_{t,b} S_{t,b}), \tag{38}$$

where $\Xi_t = \lambda / \Gamma_t^B$ is the regulatory capital requirement for banks and λ_g and λ_b represent potential rewards or penalties on the weights required by the regulator on green and brown loans, respectively.[14] Finally, we rewrite the value function to find Γ_t:

$$\begin{aligned} V_t &= \lambda \nu_t (\lambda_g Q_{t,g} S_{t,g} + \lambda_d Q_{t,b} S_{t,b}) + \Delta \beta E_t \left\{ \Lambda_{t,t+1} \Omega_{t+1} R_{t+1} N_t \right\} \\ \Gamma_t^B N_t &= \nu_t \Gamma_t^B N_t + \Delta \beta E_t \left\{ \Lambda_{t,t+1} \Omega_{t+1} R_t N_t \right\} \\ \Gamma_t^B &= \frac{1}{1 - \nu_t} \Delta \beta E_t \left\{ \Lambda_{t,t+1} \Omega_{t+1} R_{t+1} \right\}. \end{aligned} \tag{39}$$

We close this part of the model with the aggregate law of motion for the net worth of bankers:

$$N_t = \theta_B [(R_{t,g} - R_t) Q_{t-1,g} S_{t-1,g} + (R_{t,b} - R_t) Q_{t-1,b} S_{t-1,b}] + (\theta_B R_t + \omega) N_{t-1}, \tag{40}$$

with $\omega \in [0; 1)$ the proportion of funds transferred to entering bankers.

2.4 Public Authorities

2.4.1 Central Bank

The central bank follows a simple Taylor [1993] rule to set the interest rate:

$$i_t - \bar{\imath} = \rho_c (i_{t-1} - \bar{\imath}) + (1 - \rho_c) \left[\phi_\pi (\pi_t - \bar{\pi}) + \phi_y (Y_t - Y_{t-1}) \right], \tag{41}$$

where $\bar{\imath}$ is the steady state of the nominal rate i_t, $\rho_c \in [0, 1)$ is the smoothing coefficient, $\phi_\pi \geq 1$ is the inflation stance penalizing deviations of inflation from the steady state, ϕ_y is

[14] For instance, if $\lambda_g < \lambda_b$ banks will need to hold less capital for loans they grant to green firms compared to brown firms. Note that the actual capital ratio thus also depends on the risk-weights assigned to each asset, consistent with Basel III framework.

the output gap stance penalizing deviations of output from its previous period level Y_{t-1}. Moreover, the relationship between the nominal and the real interest is modeled through the Fisherian equation:

$$i_t = R_t E_t \{\pi_{t+1}\}. \tag{42}$$

We match the observed level of nominal interest rate using the simulated method of moments with the German 10-year Bund as an observable.[15] The estimation leads to a steady sate value of about 1% annually over the sample period. This drastically limits the scope of conventional monetary policy, as the central bank can not set its nominal interest rate below zero.[16]

In addition to setting the nominal interest rate, the central bank conducts open market operations. Within our framework, it will be able to buy and sell assets that are otherwise held by financial intermediaries. We will explain in section 2.7 how public financial intermediation (i.e. QE) works in this model.

2.4.2 Government

The government sets a budget constraint according to the following rule:

$$T_t + \tau_{et} E_t + RP_{t,g}\psi_{t,g}K_{t,g} + RP_{t,d}\psi_{t,b}K_{t,b} = G_t, \tag{43}$$

with public expenditure G_t finding its source from taxes T_t, revenues from the price of carbon $\tau_{et}E_t$ and from public financial intermediation on both green and brown firms $RP_{t,g}\psi_{t,g}K_{t,g}$ and $RP_{t,b}\psi_{t,d}K_{t,b}$ (with $RP_{t,k}$ the spread between each sector's risky rate and the riskless rate, also referred to as risk premia). Government spending is also assumed to be a fixed proportion of the GDP:

$$G_t = \frac{\bar{g}}{\bar{y}} Y_t. \tag{44}$$

2.5 Normalization and Aggregation

Factors and goods markets clear as follows. First, the market-clearing conditions for aggregate capital and investment in the two sector economy read as: $K_t = \sum_k g(\varkappa) \int_0^1 K_{jt,k} dj$ and $I_t = \sum_k g(\varkappa) \int_0^1 I_{jt,k} dj$, respectively. Second, global aggregate emissions and aggregate emissions cost are two weighted sums of sectoral emissions $E_t = \sum_k g(\varkappa) \int_0^1 E_{jt,k} dj$, and sectoral emissions cost $Z_t = \sum_k g(\varkappa) \int_0^1 Z_{jt,k} dj$, respectively. Finally, the resource constraint

[15] At the steady state, inflation is normalized to 1, so that $i_t = R_t$.

[16] Since we do not model banks' holding of reserves at the central bank.

of the economy features capital adjustment and abatement costs:

$$Y_t = C_t + G_t + I_t + \sum_k g(\varkappa)[f_k(.)(I_{t,k})] + \sum_k g(\varkappa)\Delta^P_{t,k} Y_t + Z_t. \tag{45}$$

2.6 Climate Externality and Financial-Economics Inefficiencies

Retrieving the optimal allocation where the environmental cost is internalized by the central planner requires setting the carbon price in the decentralized equilibrium equals to the social cost of carbon found in the centralized problem. To keep the framework tractable and without a loss of generality, we solve the centralized problem for households and firms, given an allocation of investment, capital, financial intermediaries net worth and deposit as these do not enter the social cost of carbon derivation.[17]

2.6.1 Competitive Equilibrium

To pin down the optimal carbon policy, we solve for the Competitive Equilibrium (CE*). The CE* in this economy is defined as follows:

Definition 1 *A competitive equilibrium consists of an allocation* $\{C_t, K_{t,k}, E_{t,k}, X_t, T^o_t\}$*, a set of prices* $\{P_t, P_{t,k}, R_t, R^k_{t,k}, W_{t,k}\}$ *and a set of policies* $\{\tau_{et,k}, T_t, B_{t+1}\}$ *such that:*

- *the allocation solves the consumers' and firms' problems given prices and policies,*
- *the government budget constraint is satisfied in every period,*
- *temperature change satisfies the carbon cycle constraint in every period, and*
- *markets clear.*

Result 1 *The optimal solution sets the carbon price policy* $\tau_{et,k}$ *as an optimal policy* $\tau^*_{et,k}$*, which maximizes total welfare in equation (1):*[18]

$$\tau^*_{et,k} = g(\varkappa) SCC_t. \tag{46}$$

with SCC_t *the social cost of carbon:*

$$SCC_t = \eta\beta \frac{\lambda_{t+1}}{\lambda_t} SCC_{t+1} + (\upsilon^o_1 \upsilon^o_2)\beta \frac{\lambda_{t+1}}{\lambda_t} \S^T_{t+1}, \tag{47}$$

[17]We can easily show that adding financial intermediaries as well as capital producing firms to the constraints of the centralized problem does not change change the SCC derivation.

[18]The full derivation of the CE* can be found in the technical appendix

and with

$$\S_t^T = (1-\upsilon_1^o)\beta\frac{\lambda_{t+1}}{\lambda_t}\S_{t+1}^T - \sum_k \Psi_{t,k}\varepsilon_t^{A,k}\frac{\partial d(T_t^o)}{\partial T_t^o}K_{t,k}^{\alpha}(\Gamma_t L_{t,k})^{1-\alpha}. \tag{48}$$

2.6.2 Departing from the Competitive Equilibrium to Meet Climate Goals

Definition 2 *Public authorities, however, do not optimally set the carbon price as highlighted in definition 2. In the EU, public authorities target a level of emissions that is consistent with their objective of a 55% emissions reduction by 2030. In practice, this means gradually increasing the cost of carbon through the reduction of emissions quotas distributed to firms within specific sectors. We model this situation by assuming that the cap set by the fiscal authority follows a decreasing trend, implying a growing price of carbon. The resulting carbon price can then be hit by exogenous shocks, to account in a 'stylized' way for price fluctuations on the ETS market:*

$$E_t = Cap_t \tag{49}$$

with $Cap_t = Cap/\Gamma_t^{Cap}$*. Equivalently, a cap on emissions translates to a price of carbon such that:*

$$\tau_{et,k} = Carbon\ Price_t, \tag{50}$$

where $Carbon\ Price_t = \varepsilon_t^{\tau}\Gamma_t^{Price}\ Carbon\ Price$*. In this case,* Γ_t^{Price} *is a trend on the carbon price that is proportional to the trend on the cap* Γ_t^{Cap} *and is consistent with the desired emissions reduction implemented through the cap policy.* ε_t^{τ} *represents the ETS price shock.*[19]

This stylized representation of the implementation of a permit market allows us to find theoretical fiscal pathways consistent with the EU climate objectives.

2.6.3 Welfare Distortion

Definition 3 *The welfare distortion arises when there is a difference between the optimal environmental policy and the targeted policy consistent with the EU objectives:*

$$\tau_{et,k}^* \neq \tau_{et,k} \tag{51}$$

[19] In our setup, carbon prices variations at the business cycle frequency are mainly driven by exogenous market forces. While sudden changes in abatement efficiency (i.e. the abatement cost) could in theory be a source of carbon price volatility, we abstract from considering this mechanism as there is a lack of empirical evidence and data availability (at the business cycle frequency) on abatement costs.

When $\tau_{et,k}$ moves away from $\tau^*_{et,k}$, the loss in welfare grows:[20]

$$\Delta_{\{\tau-\tau^*\}} Welfare < 0 \tag{52}$$

where the welfare could be decomposed as follows:

$$\begin{aligned} Wedge_{C_k} \propto & (1-g)\varepsilon_t^{A,k}(\Gamma_t^{1-\alpha}\bar{L}^{1-\alpha})(d(T_t^o)K_{t,k}^\alpha - d(T_t^o)^* K_{t,k}^{\alpha\,*}) - (f(K_{t,k}) - f(K_{t,k})^*) \\ & - ((\Gamma_t^{1-\alpha}\bar{L}^{1-\alpha})(d(T_t^o)K_{t,k}^\alpha f(\mu_{t,k}) - d(T_t^o)^*)K_{t,k}^{\alpha\,*} f(\mu_{t,k})^*) \end{aligned}$$

Proposition 1 *Macroprudential climate risk-weights loosening the constraint on bank lending to the green sector can reduce the welfare loss on consumption, while addressing climate-related financial risk.*[21]

Implementing a higher policy rate compared to an optimal policy clearly decreases damages from temperature to production $d(T_t^o) < d(T_t^o)^*$. However, abatement is costlier under the higher policy rate. This results in a loss of welfare, but prevents potential climate risks in the future that are not internalized by firms. The climate risk-weights macroprudential policy, which will lower (increase) the capital requirement for green (brown) assets, will in turn trigger a rise (decrease) in green (brown) firms' capital. As green firms are less subject to the carbon price, the increase in the relative size of the green sector in total output will lead to a welfare gain.

2.6.4 Risk Premium Wedge

Volatility in risk premia $\mathrm{RP}_{t,k}$, defined as the difference between expected returns on risky assets $R_{t,k}$ and the return on the riskless asset R_t, could alter monetary policy transmission (Doh et al. [2015]).

Definition 4 *When the carbon price is set through a market for carbon permits, it induces price uncertainty that is detrimental to firms. Ultimately, it affects the marginal cost of firms as well as the price of capital, and leads to movements in risk premia. In the case of a positive carbon price shock, the marginal cost of firms increases as they are now subject to*

[20] A full decomposition of the welfare effect is presented in appendix section C.5.

[21] As detailed in section 2.7 and shown in figure 4, macroprudential policy arises as a tool to mitigate climate risk to the financial sector. While primarily intended to ensure financial stability, it also dampens the welfare effect of an increasing carbon price.

higher CO_2 prices. This in turn could raise the risk premium:[22]

$$RP_{t,k} = R_{t,k} - R_t \tag{53}$$
$$= f(\Psi_{t,k}, Y_{t,k}, K_{t,k}, Q_{t,k}) - R_t \tag{54}$$

Proposition 2 *Volatility in risk premia stemming from carbon price fluctuations could potentially distort the functioning of monetary policy operations. Short-term monetary policies (QE rules that react to changes in risk premia) can prevent this situation and ensure financial stability.*

The risky rate reacts to changes coming both from the firms' side and the financial side. In this case, the goal is to cut the link between the rise of the marginal cost (triggered by an increase in the carbon price) and the impact on the risk premium. One way to do so is to act on the financial side to compress the risk premium. Similar to models where a rise in risk premia comes from an exogenous shock on the quality of capital (e.g. crisis simulation in Gertler and Karadi [2011]), the central bank is able to offset this effect by intervening in the loan market.

2.7 Set of Policies

Environmental Policy

When acting optimally, the decentralized planner would set the environmental policy as shown in result 1 ($\tau^*_{et,k}$ is set equal to the social cost of carbon $g(\varkappa)SCC_{t,k}$). However, as highlighted in the previous section, the EU authorities deviate from the optimal policy and set the environmental policy to be consistent with their net-zero emissions reduction objective ($\tau_{et,k} \neq \tau^*_{et,k}$).

Sectoral Macroprudential Weights

There is a macroprudential authority with the ability to alter the regulatory constraint weighing on banks (equation (34)) by modifying risk-weights on loans.

Environmental, social, and corporate governance (ESG) criteria are increasingly valued by both investors and authorities. As these criteria are also gaining importance in firms' credit ratings (Escrig-Olmedo et al. [2019] and Carbone et al. [2021]), it will likely impact

[22] The impact is symmetric in the case of a negative carbon price shock. Furthermore, whether the shock is positive or negative, it implies higher volatility for the marginal cost and the risk premium.

banks' portfolio allocation. On the regulatory side, macroprudential authorities are starting to assess how they could consider climate risk within their frameworks. Recently, the Basel Committee [2021] issued a press release stating that "The Committee is taking a holistic approach to addressing climate-related financial risks to the global banking system. This includes the assessment and consideration of disclosure, supervisory and regulatory measures." Within our framework, this would mean that firms with a low carbon intensity would carry a lower risk-weight in the RWA methodology, while carbon-intensive firms would carry a higher risk-weight. In our view, there are two means by which this could materialize. Either ESG criteria would become so important in standard credit ratings such that it could lead to environmentally friendly firms getting a higher rating, and thus a lower risk-weight in banks' regulatory constraint. For instance, a green firm could see its rating upgraded from BBB+ to A-, implying a 25 percent drop in the risk-weight associated with this firm in banks' regulatory capital constraint. On the other hand, a carbon-intensive firm could see its rating downgraded from BBB- to BB+, implying a 25 percent increase in the risk-weight associated with this firm.[23] In this case, this change in the importance of ESG criteria in credit ratings would endogenously transmit to macroprudential policy, and ultimately to banks' portfolio allocation. Another possibility would be that macroprudential authorities apply an additional risk-weight related to the carbon intensity of firms. It could for instance multiply the risk-weight related to the credit rating of a firm by a climate risk-weight related to the environmental performance of a firm. In our setup, implementing climate risk-weights in the spirit of Basel III, would mean decreasing λ_g by 25 percent (i.e. $\lambda_g = 0.75$) and increasing λ_b by 25 percent (i.e. $\lambda_b = 1.25$).[24] This will loosen (tighten) the regulatory constraint on banks with respect to the green (brown) sector, triggering an increase (decrease) in loans to green (brown) firms. In addition to addressing climate-related financial risk, it would also support the transition to a greener economy.

Quantitative Easing

QE in this model can be both a short-term or a medium/long-term instrument. In the short term, the central bank can purchase or sell bonds as part of open market operations to ensure the smooth transmission of monetary policy. In this case, we model it as a QE rule, in the spirit of Gertler and Karadi [2011]. We will show quantitatively how QE rules

[23] Please refer to the high-level summary of Basel III reforms (Basel Committee [2017]) for a detailed description of the RWA methodology.

[24] We consider this to be our baseline scenario, where both green and brown bonds held by financial intermediaries are mainly at the lower rank of investment grade bonds (i.e. BBB+ to BBB-). We also investigate other cases in our robustness exercises, where climate risk-weights applied are higher.

targeting risk premia can offset the inefficiency stemming from the uncertainty over the carbon price. In the long term, the central bank can also implement LSAP programs, where it decides to buy a predefined portion of assets over a determined period of time. Much like the Corporate Sector Purchase Program in the EA, the central bank has the ability to finance non-financial firms in order to reduce corporate spread, steer private investment, and ultimately keep inflation within range of its target. In a complementary exercise, we will assess how green LSAP programs differ from conventional brown LSAP programs.

Then for each type of firm k we now have:

$$Q_{t,k}S_{t,k} = Q_{t,k}S_{pt,k} + Q_{t,k}S_{gt,k}, \tag{55}$$

with $Q_{t,k}S_{gt,k}$ the total real value of loans to firms of type k held by the central bank. $Q_{t,k}S_{pt,k}$ is the total real value of loans to firms of type k held by financial intermediaries, as defined in section 2.3. As in Gertler and Karadi [2011], we model this intervention by assuming that the central bank holds a portion $\psi_{t,k}$ of total loans to non-financial firms belonging to each sector:[25]

$$Q_{t,k}S_{gt,k} = \psi_{t,k}Q_{t,k}S_{t,k}. \tag{56}$$

To address the inefficiency stemming from carbon price uncertainty, we will assume that, for each sector, the central bank follows a counter-cyclical credit policy rule that reacts to the variations in the expected spread ($E_t\{\mathrm{RP}_{t+1,k}\} = E_t\{R_{t+1,k} - R_{t+1}\}$) in order to decide the share of assets $\psi_{t,k}$ it holds. This rule is defined as follows:

$$\psi_{t,k} = \phi_k^s(E_t\{\mathrm{RP}_{t+1,k}\} - \bar{\mathrm{RP}}_k). \tag{57}$$

Note that in our baseline model $\psi_{t,k} = 0$ so that the central bank allows financial intermediaries to be the sole source of financing for firms.

3 Solution Method

3.1 Balanced Growth Path

In our economy, the labor-augmenting technology grows at rate Γ_t. As a number of variables (e.g. output, emissions, investment, ...) will not be stationary, we need to de-trend

[25] For simplicity, we abstract from monitoring costs.

the model.[26] In the appendix subsection C.7 we present the de-trended economy, where all variables are stationary along an existing balanced growth path. The variables of our economy growing at the same rate Γ_t include: output per capita $Y_{t,k}$, investment per capita $I_{t,k}$, consumption per capita C_t, government spending G_t, lump sum taxes T_t, capital per capita $K_{t,k}$, emissions $E_{t,k}$, abatement costs $Z_{t,k}$, stock of emissions X_t, temperature T_t^o, debt to households B_t, net worth N_t, and the banks' value function V_t^B.

3.2 Model Solving and Methods

To solve for the medium/long-run pathway scenarios, we use the extended path algorithm, which allows us to integrate both deterministic trends and stochastic shocks. This approach maintains the ability of deterministic methods to provide accurate accounts of non-linearities, while usual local approximation techniques do not perform as well under the presence of such non-linearities (Adjemian and Juillard [2013]). Furthermore, we account for uncertainty and compute confidence intervals along the net-zero transition pathways. We rely on the Monte Carlo method and simulate 2000 series for both stochastic shocks (i.e labor-augmenting technology and carbon price shocks) around their deterministic trends. As for addressing short-term business cycle implications of the ETS price volatility, we use second-order perturbation methods as they are usually performed in the macro-finance literature to retrieve impulse response functions.

3.3 Data and Fitting Strategy

As we will study the role of the central bank and macroprudential authority, we calibrate and estimate the model on the EA, even though the environmental ETS policy is set at the EU level. This is without a loss of generality, since all countries in the EA are members of the EU.

In order to best fit our model to real data,[27] we rely on the SMM (Duffie and Singleton [1993]) to estimate key structural parameters of our economy (table 4). In the spirit of Jermann [1998] we match the first and second moments of: output growth, investment growth, and consumption to output growth. As we are also interested in the financial and environmental sectors, we match the first moments of the real riskless and risky rates, the capital ratio of banks, the emission to output ratio, the global stock of carbon, and the ETS

[26] This is also necessary to estimate our key structural parameters using the SMM.

[27] For macro-finance data, we match first and second moments using EA data between 2000 and 2020. All data sources are summarized in table 5.

price level (at the beginning of 2021), as well as the difference between green and brown firms' marginal costs. We estimate the following key structural parameters: $\{\eta_{A_k}$, ρ_{A_k}, $\frac{\bar{g}}{\bar{y}}$, η_i, β, γ_Y, h, α, δ, θ_g, θ_d, E^*, φ_k, Carbon Price, λ, $\omega\}$, using the Metropolis–Hastings algorithm for the Markov Chain Monte Carlo over 5 chains of 2000 draws. The remaining parameters are calibrated and their values are reported in table 1, table 2, and table 3.

3.3.1 Calibration

For parameters related to business cycle theory, their calibration is standard: the share of hours worked per day is set at one third in each sector and the coefficient of relative risk aversion σ in the CRRA utility function is set at 2, as argued by Stern [2008] and Weitzman [2007].

Regarding environmental components, we calibrate the damage function according to Nordhaus and Moffat [2017].[28] The global temperature parameters υ_1^o and υ_2^o are set following Dietz and Venmans [2019] to pin down the 'initial pulse-adjustment timescale' of the climate system.[29] We use sectoral data made available by the Transition Pathway Initiative to set the share of the green sector $\varkappa$ at 30 percent.[30] Abatement parameters $\theta_{b,1}$, $\theta_{b,2}$, and $\theta_{g,2}$, which pin down the abatement costs for each sector, are set as in Heutel [2012]. We then proceed to set $\theta_{g,1}$ to match the drop in emissions induced by the introduction of the carbon price policy in the EA. More precisely, we retrieve the value of $\theta_{g,1}$ in such a way so as to be consistent with a reduction of emissions of 14.3 percent between 2009 and 2020,[31] which is associated with an increase in the carbon price from 0 to 30 euro (the price of ETS at the end of 2020). In our model, this leads to a value of $\theta_{g,1}$ of 0.02, which means that the abatement technology is cheaper in the green sector. The decay rate of emissions δ_x is set at 0.21 percent as in Heutel [2012].

As for the financial parameters, we set the probability of remaining a banker θ_B at 0.98, meaning that 2 percent of bankers default every quarter, which is slightly less than in Gertler and Karadi [2011]. Δ is a parameter that introduces a different discount factor in the bankers' objective function relative to households and is set to 0.99. This implies that bankers are slightly more impatient than households. Finally, the monetary rule parameters are set as in Smets and Wouters [2003].

[28] We perform a sensitivity analysis using values from Dietz and Stern [2015] and Weitzman [2012] in the next section.

[29] We also perform a sensitivity analysis for υ_2^o.

[30] What we consider green in our model is a sector with a carbon performance that allows for an emission target aligned with the Paris Agreement of 2 degrees Celsius or below.

[31] We remove the first and last years of data.

Regarding the carbon price shock, we calibrate the standard deviation using ETS data (futures prices). We find a standard deviation of about 0.18 on a quarterly basis.

3.3.2 Estimation

Parameters estimated through the SMM are reported in table 4, while the empirical moments matched are reported in table 5. Although we only rely on a shock to the labor-augmenting technology, all parameters are well identified and the model is able to match empirical moments for the EA.

More precisely, the depreciation rate of physical capital is estimated at 2.5 percent in quarterly terms, the government spending to GDP ratio at 28 percent, and the capital intensity in the production function α at 0.33. All these estimates are quite standard within the macroeconomic literature. The inverse elasticity of net investment to the price of capital η_i is estimated at 1.7354, in line with the value chosen by Gertler and Karadi [2011]. The parameter b, which allows us to pin down the discount factor, is set at 0.02. This ensures that we match the steady state real interest rate of about 1 percent (the mean rate of 10-year German Bund over the sampled period). Habits in consumption are found to be rather low (0.22) compared to the estimated value of Smets and Wouters [2003].

To replicate the global level of carbon stock in the atmosphere (i.e. 840 gigatons), the level of the rest of the world's emissions E^* is estimated at 3.37. Furthermore, as argued by De Haas and Popov [2019], CO_2 emissions intensity differs largely between sectors and industries. We use carbon intensity parameters φ_b and φ_g to match the observed ratio of emissions to output for the EA, which is at 21 percent.[32] Assuming that the carbon intensity in the green sector is approximately one third of what it is in the brown sector, we find that $\varphi_b = 0.29$ and $\varphi_g = 0.09$.

The value of θ_d, the brown firms' marginal cost parameter, is set as in Smets and Wouters [2003] to replicate the mean markup and marginal cost levels observed in the economy. On the other hand, θ_g is estimated to match the green marginal cost, which is—as argued by Chan et al. [2013] and Chegut et al. [2019]—6 percent higher than the brown firms' marginal cost.

The parameter shaping the leverage of banks $\bar{\lambda}$ is estimated at 0.0176 to generate a spread of 80 basis points between risky and riskless assets, consistent with Fender et al. [2019]. The authors also find that the spread between green and brown bonds recently

[32] We compute this value as the number of kCo2 per dollar of GDP using emissions data from the Global Carbon Project and GDP data from Eurostat.

disappeared. Thus, we target the same steady state for R_g and R_d.[33] The proportional transfer to entering bankers ω is found to be around 0.006, allowing us to match a capital ratio of approximately 14.4 percent in the EA.

Finally, for the TFP shock, standard deviation and persistence are estimated at 0.006 and 0.78, which are both in line with previous estimates of Smets and Wouters [2003] for the EA.

4 Quantitative Analysis

In the EU, the carbon price resulting from the ETS cap policy is subject to high volatility. We use ETS futures weekly prices to retrieve the mean standard deviation over the period, before converting it to a quarterly level. We then set the standard deviation of the ETS carbon price σ_{ETS} to this value for all pathway simulations and exercises we conduct.

With respect to the long-term inefficiency (i.e. the welfare loss), we perform stochastic transition pathway simulations,[34] where we include stochastic shocks on both the price of carbon and the TFP around their respective deterministic growth rate. We perform 2000 Monte Carlo simulations to construct 95 percent confidence intervals around the deterministic trends for both the output and the carbon price needed to achieve the net-zero pledge. We then investigate the role that green macroprudential policy—which favors the green sector over the brown sector—could play in mitigating the welfare wedge, while ensuring financial stability.

Turning to the short-term inefficiency (i.e. risk premia distortion), we perform stochastic simulations to investigate the impulse responses to a shock to the price of carbon on risk premia and inflation, and highlight how the central bank could take into account this type of transition risk within its framework.

4.1 Fiscal Environmental Policy Scenario

The goal of this section is to present and analyze theoretical fiscal pathways consistent with the EU objective for 2030.[35] We first find the trajectory of the carbon price that leads to the desired reduction in emissions (i.e. a 55 percent emissions reduction relative to the

[33] This is also in line with recent findings of Flammer [2021] with respect to the so called "Greenium" puzzle (i.e. $R_g < R_d$). In this paper, she finds no evidence for the existence of a Greenium.

[34] We compare two scenarios: a) the carbon policy is consistent with the net-zero objective and b) the carbon policy is consistent with the optimal social cost of carbon.

[35] In this section, as the main focus is long-term transition pathways, we do not consider nominal rigidities in prices.

1990 level, which corresponds to a 33 percent reduction relative to the 2020 level). We then highlight the impact of sub-optimal carbon pricing policies on welfare.

4.1.1 Growth, carbon price, and the EU objectives

Figure 5 shows carbon price trajectories (according to two different growth scenarios) consistent with being on track for achieving the net-zero objective in the EU. The blue dashed line is the central scenario with a growth trend of 0.8 percent, corresponding to the average real growth rate per capita in the EA from 2000 to 2020. The orange dotted line is a scenario with a more optimistic growth trend of 1.2 percent. We also add stochastic components drawn from random disturbances to the TFP and the carbon price. The shaded blue and orange areas are 95 percent confidence intervals retrieved over the 2000 Monte Carlo draws. This allows us to account for uncertainty in output growth and the carbon pricing trajectory.[36] Depending on the growth scenario, reducing emissions by 55 percent compared to 1990 level would require a mean carbon price between 350€ and 375€ per ton of CO_2. Accounting for uncertainty, the price is found to fluctuate between 200€ and 500€, meaning that the target could be either undershot or overshot. Note that this large confidence interval is computed assuming that future volatility can be inferred from past volatility. However, EU countries are considering measures to reduce price fluctuations in the ETS market,[37] which could lead to a lower standard deviation in the future. This exercise provides evidence that such measures are needed if the EU authorities want to improve their ability to meet their emission reduction objective. Furthermore, we also find that the price of carbon needs to follow the growth of output to be able to shrink the flow of emissions to the desired level. It is worth noting, however, that our model takes the abatement technology as given. With improvements in technology, the EU could reach the same target with a lower carbon price, but the mechanisms to trigger this improvement in the abatement technology are left for further research.

Figure 6 uses the central growth scenario (i.e. 0.8 percent growth rate) to compare the net-zero trajectory with a carbon market that exhibits uncertainty (blue solid line and shaded area) and a market that yields a completely deterministic carbon price (purple dotted line and shaded area). This is similar to comparing a cap policy with a tax policy. We find that a carbon tax like system, where volatility is controlled, would allow for reaching the net-zero

[36] Where trend growth in output and carbon prices are anticipated, but shocks can distort these deterministic processes in the short run.

[37] A carbon price floor has been implemented in the Netherlands and is currently under consideration in Germany. The EU Market Stability Reserve was also introduced to regain some control over the carbon price.

objective with certainty. However, a cap and trade policy ensures that emissions reduction take place efficiently, as firms are able to trade permits while a tax system imposes a fixed reduction in emissions to all firms. In addition, Karp and Traeger [2018] show that, when considering a stock pollutant, a cap market guarantees efficiency gains (compared to a tax system) when the economy is subject to technology shocks that shift the marginal abatement cost curve and the social cost of carbon.

The ambitious net-zero goal would have several implications on output and consumption alike. In figure 7, we show that uncertainty in carbon pricing does not significantly alter consumption pathways and therefore does not alter the welfare, as shown in the case of the certainty equivalence in Golosov et al. [2014]. Carbon price shocks do not propagate to the households as, on one hand, the stochastic discount factor—which is the central part in asset pricing and consumption smoothing mechanisms—is not directly impacted by the carbon pricing, and, on the other hand, the relative risk aversion is set different to 1 (the log utility case). In our setup, climate risk is not directly captured within the utility function, restraining the carbon price shock from propagating to consumption and welfare.[38] As such, we run deterministic transition pathway simulations instead of stochastic transition pathway simulations for the remaining welfare analysis.

4.1.2 Welfare implications

The first two plots in figure 8 display the trajectory of the environmental policy consistent with the EU objective compared to the optimal environmental policy for both output and emissions. The optimal policy (i.e. setting the carbon price equals to the SCC) trajectory is not able to meet the net-zero pledge. The carbon price needed to achieve net-zero is found to be significantly higher than the SCC, thus altering the welfare pathway. Several key factors are in play. First, the fact that the environmental externality is a slow moving variable pushes the social planner to further its intervention at a late stage when the stock of carbon has significantly accumulated, and has become a major threat. Second, the absence of tipping points, which would force the social planner to account for uncertainty over the climate damages, would obligate the social planner to increase its actions by increasing the SCC (Dietz et al. [2021]). Third, the household utility objective function does not capture the effects of climate change directly, which would impact the SCC (Barrage [2020] and

[38] While integrating climate risk as a dis-utility would allow for carbon price shocks to propagate to the welfare, we do not model it in this paper and leave it for future research.

Benmir et al. [2020]).[39] Finally, in recent work, Cai and Lontzek [2019], Traeger [2021], and Van den Bremer and Van der Ploeg [2021] both show that accounting for uncertainty in climate dynamics could increase the inherent level of the SCC. This increase in the carbon price, which would be welfare enhancing in our framework, is still, however, not sufficient to meet the net-zero emissions reduction goal. We show that the price difference between the optimal SCC and the net-zero ETS induced carbon price needed to reach the target (the "Extra Carbon Price") is about 300€ higher by the end of 2030. While we do not explicitly model tipping points in the damage function, we perform a sensitivity analysis both on the climate damages specification and climate dynamics.

As reported in our sensitivity analysis (table 6), the optimal price of carbon depends on the specification of damages. We find carbon prices between 31.2€ to 144.1€ for different calibrations found within the literature. Furthermore, in the spirit of Traeger [2021], we perform a sensitivity analysis over the parameter υ_2^o, which drives the climate dynamics for temperature. We show that for a higher value of υ_2^o, temperature by 2030 could double, but the implied SCC (under both Nordhaus and Dietz damage specifications) would still be insufficient to obtain the desired emission reduction to be on track for net-zero by 2030. Under the Weitzman specification, we find that setting the carbon price equals to the SCC would lead to a 45 percent emissions reduction by 2030, which is higher than the EU objective. However, the carbon price that would be able to achieve such an objective is significantly high (846.65 €), thus suggesting major issues in terms of implementation. Therefore, for the remainder of the paper, we set the climate damage parameter "b" *à la* Nordhaus and υ_2^o to the baseline value as in Dietz and Venmans [2019], as these are the closest to the ETS price at the start of January 2021 for all three estimates.

The two red plots in figure 8 show that the welfare loss increases over time as the extra carbon price continues to rise to about 300€. This deviation of the ETS carbon price from the SCC introduces a distortion with respect to the optimal allocation. By 2030, the household looses about 3 percent in consumption equivalent (CE) compared to the optimal case. We will see in the next section that this effect can be partially offset by sectoral macroprudential risk-weights.

4.1.3 Introducing Macroprudential Policy

To reduce the welfare gap induced by the sub-optimal policy, we investigate the role macroprudential policy could play. We present transition pathway scenarios where the

[39] Benmir et al. [2020] show that the SCC increases when households account for the externality within their utility function ($u_{xc} \neq 0$).

macroprudential authority varies regulatory risk-weights on loans granted to the green and the brown sectors by banks. While there is not yet such a policy in the EU, regulators are increasingly taking into account climate risk (see section 2.7).

In figure 9, we present two net-zero emissions reduction scenarios: i) the scenario where macroprudential policy is neutral (i.e. $\lambda_g = 1$ and $\lambda_b = 1$) in blue, and ii) the scenario where a green macroprudential policy is implemented by the regulator in green (i.e. $\lambda_g \underset{t \to 2030}{\longrightarrow} 0.75$ linearly, while $\lambda_b \underset{t \to 2030}{\longrightarrow} 1.25$). We show that favoring the green sector over the brown sector in banks' regulatory constraint leads to an increase in the green capital (8.3 percent) and a decrease in the brown capital (4.8 percent) by the end of 2030, with respect to the scenario where risk-weights are left unchanged. The implementation of green macroprudential policy thus amplifies the rise (drop) in green (brown) capital induced by the rising carbon price along the transition. Compared to the neutral macroprudential policy case, increasing the capital stock in the green sector reduces the welfare loss (of about 1 percent CE). Intuitively, the increasing carbon price triggers a substitution between brown and green production, as the green sector is less emission intensive. Favoring the green sector in the RWA policy reinforces this substitution effect by tilting investments toward the green sector, leading to an increase in output.

In figure 10, we investigate the case where the macroprudential authority favors the brown sector over the green sector to avoid a disorderly transition. The goal would be to attenuate the impact of the rising carbon price on the brown sector, as the current share of the brown sector is higher than the share of green sector (70 and 30 percent respectively). The brown macroprudential policy is displayed in brown (i.e. $\lambda_g \underset{t \to 2030}{\longrightarrow} 1.25$ linearly, while $\lambda_b \underset{t \to 2030}{\longrightarrow} 0.75$). With sectoral shares held constant, this policy would lead to a lower welfare loss by the end of 2030 than in the case of the green macroprudential policy. The RWA policy reduces the substitution effect stemming from the environmental fiscal policy. At the aggregate level, the need for investment is lower, as the substitution effect is weaker than when macroprudential policy favors the green sector. Although output decreases relative to the green macroprudential policy scenario, welfare improves as investment spending is proportionally lower.

In figure 11, we compare green and brown macroprudential policies, while assuming that the share of the green sector in the economy increases from 30 percent to 50 percent by the end of 2030.[40] With an increasing share of the green sector,[41] both types of macroprudential

[40]These results are further reinforced if the increase in the share of the green sector is greater than 50 percent.

[41]In this setting, we exogenously change the share of the green sector over the 10 year transition period. One could endogenously model this shift in the share of the green sector. We leave this for future work.

policies induce a substitution effect between the two sectors, which otherwise would not arise in the case of brown macroprudential policy (as shown previously in figure 10). In this case, green macroprudential policy is able to close the welfare wedge by the end of 2030. Two main factors are at play. First, as the share of the green sector grows, required investments in abatement decrease, thus increasing consumption. Second, green macroprudential policy induces lower investment costs in green capital, which at the aggregate level boosts consumption. Along the transition to a greener economy, favoring green firms in banks' capital requirements rules would ease the welfare burden on households, by lowering transition costs for firms. However, the main challenge would be to identify green firms in practice. As highlighted in Ehlers et al. [2020], there is a need for a 'green label' at the firm-level for companies committed to the net-zero transition, as opposed to the current project-based green labels.

As a robustness exercise, we also report in table 7 the steady state impacts of various macroprudential policy settings. We investigate several risk-weights combinations, where macroprudential policy is conducted as a one off. We consider a carbon price of about 300€ (the net-zero implied price by 2030). We then compare three scenarios: i) the model following the optimal policy ii) the model with a carbon price consistent with the net-zero target and no macroprudential policy iii) the model with a carbon price consistent with the net-zero target and various macroprudential policies. The robustness exercise shows that, the more the macroprudential authority decreases the risk-weight on green loans (while increasing the risk-weight on brown loans), the smaller the consumption loss is compared to the optimal. It would be possible to completely offset the consumption loss, but it would require drastic changes in risk-weight, which could threaten financial stability.

4.2 Risk Premia Stabilization

To offset the distortion of risk premia stemming from carbon price volatility, we assess the effectiveness of short-term QE rules set by the central bank.

The simulation reported in figure 12 presents the responses of risk premia to a positive shock to the carbon price level. We first show how risk premia react to the volatility in the ETS market. As the EU decided to implement its environmental fiscal policy through carbon permits, there is an inherent variance in the price of carbon.[42] Estimating the standard deviation of the shock on the ETS series and simulating the model allow us to analyze how these unexpected variations in the carbon price could affect firms and banks.

[42] Table 8 displays the moments of risk premia, marginal costs, and inflation for both sectors following a positive shock on carbon prices.

The blue line shows the reaction of risk premia in both the green and brown sectors following a positive shock on the carbon price. The shock leads to an increase in risk premia of about 10 basis points annually. This rise in risk premia could lead to financial instability and thus distortion in the transmission of monetary policy. To restore the equilibrium in risk premia, monetary policy could rely on quantitative easing rules (as a 'fire-fighting' tool), which would react to changes in the level of the risk premium. As such, the central bank would have the ability to substitute to financial intermediaries in financing either green or brown firms. This intervention will lead to a temporary increase in the central bank balance sheet.

More specifically, we compare two scenarios: i) a model where the central bank does not implement QE rules, ii) a model where the central bank implements QE rules with various degrees of reaction. We show that the increase in spreads could be offset by an increase in asset purchases, where the intensity of the reaction of the central bank is represented by the parameter ϕ_k^s. For instance, asset purchases of about 0.23 percent (annually) of total assets within each sector (i.e. $\phi_k^s = 0.5$) are sufficient to almost completely offset the induced distortion in risk premia.[43] The mechanism at play here is the same as in the case of exogenous financial shocks on risk premia, except that the initial rise in risk premia is triggered by the shock on the carbon price and its subsequent effect on firms' marginal costs. Compared to the financial crisis simulation in Gertler and Karadi [2011], our carbon price shock triggers a reaction of risk premia that is smaller, but the magnitude of the intervention of the central bank is proportionally similar. By stepping in to directly lend to firms, the central bank is able to restore the equilibrium on the loans market and avoid potential negative effects coming from the rise of spreads. Table 8 confirms that the variance of risk premia is significantly reduced in the presence of QE rules. With respect to sectoral inflation, we find that central bank intervention increases inflation, though the magnitude is very small (less than 0.02 percent annually). Thus, a trade-off appears between financial stabilization and inflation control. However, in our framework, the benefits of mitigating the impact of the carbon price shock on risk premia seem to outweigh the inflationary consequences of asset purchases.

[43] We also plot the case where $\phi_k^s = 5$ and $\phi_k^s = 0.05$. We show that when the central bank purchases about 0.27 percent of both green and brown assets annually, it is able to completely offset the rise in risk premia, while a purchase of about 0.15 percent annually reduces the impact on risk premia by about half.

5 Asset Purchase Program Scenario – LSAP

To shed some light on the interest of tilting central banks portfolio toward green bonds, we simulate both transitory and permanent LSAP programs run by the central bank under two macroprudential policy scenarios. In the first case, the macroprudential authority implements climate-risk weights along the transition, while in the second case risk-weights are held constant.

5.1 Transitory LSAP

The first scenario studied is a transitory LSAP program where the central bank gradually increases the size of its balance sheet to hold around 8 percent of either green or brown total assets by 2028. Asset purchases are then reversed and holdings return to zero in approximately two years. As LSAP programs are announced by central banks before being implemented, we rely on perfect foresight simulations.

Figure 13 shows the impact of both green and brown transitory LSAP programs along the transition.[44] The main result is that there is no incentive for a central bank to purchase green rather than brown bonds as part of a LSAP program, since both programs lead to the exact same results. The reason is that green and brown bonds are seen as perfectly substitutable by banks. In this case, if the central bank favors one of the sectors in its asset purchases, the effect is completely offset by the reaction of financial intermediaries. An interesting point to note is that both green and brown transitory LSAP programs allow central banks to postpone the impact of the rising carbon price on brown capital and output by loosening the constraint on banks. If the transition to a low-carbon economy were to take place in a disorderly fashion, such LSAP programs could delay the potential negative impacts the transition might have on stranded assets.

Figure 14 shows how a transitory LSAP program focused on green bonds would interact with a sectoral macroprudential policy favoring the green sector. In this exercise, asset purchases are similar to those in the previous exercise, but the risk-weight on green loans is lowered along the transition, while the risk-weight on brown loans is gradually increased. Breaking the perfect substitution between green and brown assets allows to boost green sector capital and output compared to when macroprudential policy stays neutral over the

[44] As in the previous section, the carbon price is assumed to increase to reach the EU climate goals and trend growth is assumed to be 0.8 percent annually.

period studied.[45] Overall, this leads to a positive effect on aggregate capital and output that disappears at the end of the simulation, as the central bank unwinds its asset purchases. Thus, a transitory green LSAP program coupled with a macroprudential policy favoring the green sector exacerbates the effect of the transition induced by the rise in the carbon price, which leads to a slightly better emission to output ratio.

5.2 Permanent LSAP

The second scenario studied is a permanent LSAP program where the central bank gradually increases the size of its balance sheet to hold around 8 percent of either green or brown total assets by 2028 and keeps this proportion constant from 2028 on.

Figure 15 displays the reaction of selected variables to both green and brown permanent LSAP programs along the transition. The results are quantitatively similar to the case of a transitory LSAP, except at the end of the simulation, where brown permanent LSAP seem to be more effective than transitory LSAP to mitigate the loss in brown capital and output associated with a decarbonization of the economy.

Figure 16 shows how a permanent LSAP program focused on green bonds would interact with a sectoral macroprudential policy favoring the green sector. The interaction of the two policies gives the best results in terms of accompanying the transition to a greener economy. Compared to the case where asset purchases were transitory, a permanent LSAP program yields an effect on capital, output, and emissions that is long-lasting. Overall, the emission to output ratio is lower, since green output rises sharply while brown output decreases over the period studied. It is also important to keep in mind that results presented in this section could be further reinforced if we were to witness an increase in the share of the green sector over the transition, as exemplified in the previous section.

6 Conclusion

We develop a DSGE model with both endogenously-constrained financial intermediaries and heterogeneous firms. We then use the model to assess the implications of setting an environmental policy consistent with the net-zero target using a cap system.

We find that a price of about 350€ per ton of carbon is needed to be aligned with the net-zero target. However, the actual implementation of this price induces two inefficiencies.

[45] Similarly, Ferrari and Nispi Landi [2021] break the perfect substitutability by introducing a quadratic cost related to the holding of green bonds by banks.

The first inefficiency is linked to the need of an increasingly higher price of carbon (compared to the optimal SCC) to meet the EU targets. This decoupling generates a growing welfare loss. To address this wedge, we show that a RWA policy favoring the green sector (i.e. green macroprudential policy) is efficient in partially offsetting the welfare loss while reaching the emissions target. Furthermore, green macroprudential would allow the regulator to address climate-related financial risk.

The second inefficiency is related to the market design of the environmental fiscal policy in the EU area. The present volatility in the ETS is shown to affect firms' marginal costs and thus to alter risk premia. We find that QE rules that react to changes in risk premia are able to completely offset movements in spread levels and volatility, allowing for a smooth transmission of monetary policy, while not significantly impacting inflation.

Turning to LSAP programs, we find that macroprudential policy is needed to provide an incentive to central banks to engage in both transitory and permanent green QE. However, permanent LSAP programs yields an effect on capital, output, and emissions that is long-lasting compared to transitory LSAP programs.

More generally, we show that QE rules could be used as a short-term countercyclical tool, while sectoral macroprudential policy could play a more structural role, allowing for a smooth transition toward net-zero.

In particular, we find that green macroprudential policy strengthen the substitution effect between the two sectors, which is triggered by the environmental fiscal policy. While this result is obtained with a constant share of the green sector ($\varkappa$), increasing $\varkappa$ along the transition reinforces our findings. Intuitively, making the green sector predominant (figure 2 and figure 3), would not only decrease substantially emissions, which in turn decreases the environmental policy cost (i.e. the carbon price), it would also help achieve the sought-after decoupling of emissions and output. The emissions to output ratio $E_Y = E/Y$ falls almost linearly with an increase in the green sector share and leads to lower level of carbon price.

Many extensions could be conducted using our framework. In particular, we think that further research could be devoted to the impact of non-linearities within the financial sector on the dynamics of the model and to the role that endogenous TFP could play in fostering the emergence of greener output growth. We also believe it could be fruitful to examine how to capture the environmental quality on the welfare of households in more direct ways than in existing models.

7 Bibliography

D. Acemoglu, P. Aghion, L. Bursztyn, and D. Hemous. The environment and directed technical change. *American economic review*, 102(1):131–66, 2012. 5

D. Acemoglu, U. Akcigit, D. Hanley, and W. Kerr. Transition to clean technology. *Journal of Political Economy*, 124(1):52–104, 2016. 6

D. Acemoglu, D. Hemous, L. Barrage, P. Aghion, et al. Climate change, directed innovation, and energy transition: The long-run consequences of the shale gas revolution. In *2019 Meeting Papers*, number 1302. Society for Economic Dynamics, 2019. 5

S. Adjemian and M. Juillard. Stochastic extended path approach. *Unpublished manuscript*, 2013. 23

P. Aghion, A. Dechezleprêtre, D. Hemous, R. Martin, and J. Van Reenen. Carbon taxes, path dependency, and directed technical change: Evidence from the auto industry. *Journal of Political Economy*, 124(1):1–51, 2016. 5

K. Angelopoulos, G. Economides, and A. Philippopoulos. What is the best environmental policy? taxes, permits and rules under economic and environmental uncertainty. *CESifo working paper series*, 2010. 4

B. Annicchiarico and F. Di Dio. Environmental policy and macroeconomic dynamics in a new keynesian model. *Journal of Environmental Economics and Management*, 69:1–21, 2015. 4, 65

L. Barrage. Optimal dynamic carbon taxes in a climate–economy model with distortionary fiscal policy. *The Review of Economic Studies*, 87(1):1–39, 2020. 28

Basel Committee. High-level summary of basel iii reforms. Bank for International Settlements, Basel Committee on Banking Supervision, 2017. 21

Basel Committee. Basel committee consults on principles for the effective management and supervision of climate-related financial risks. Nov 2021. URL https://www.bis.org/press/p211116.htm. 21

M. D. Bauer and G. D. Rudebusch. The rising cost of climate change: evidence from the bond market. *The Review of Economics and Statistics*, pages 1–45, 2021. 2

J. Benhabib, R. Rogerson, and R. Wright. Homework in macroeconomics: Household production and aggregate fluctuations. *Journal of Political economy*, 99(6):1166–1187, 1991. 9

G. Benmir, I. Jaccard, and G. Vermandel. Green asset pricing. *ECB Working Paper*, 2020. 2, 29

V. Bosetti, M. Maffezzoli, et al. Occasionally binding emission caps and real business cycles. *IGIER working paper*, 2014. 4

Y. Cai and T. S. Lontzek. The social cost of carbon with economic and climate risks. *Journal of Political Economy*, 127(6):2684–2734, 2019. 3, 10, 29

S. Carattini, G. Heutel, and G. Melkadze. Climate policy, financial frictions, and transition risk. *NBER Working Paper*, 2021. 3, 4

S. Carbone, M. Giuzio, S. Kapadia, J. S. Krämer, K. Nyholm, and K. Vozian. The low-carbon transition, climate commitments and firm credit risk. *ECB Working Paper*, 2021. 20

C. Carvalho and F. Nechio. Factor specificity and real rigidities. *Review of Economic Dynamics*, 22:208–222, 2016. 5, 6, 8

H. S. Chan, S. Li, and F. Zhang. Firm competitiveness and the european union emissions trading scheme. 2013. 8, 25

A. Chegut, P. Eichholtz, and N. Kok. The price of innovation: An analysis of the marginal cost of green buildings. *Journal of Environmental Economics and Management*, 98:102248, 2019. 8, 25, 43

L. J. Christiano, M. Eichenbaum, and C. L. Evans. Nominal Rigidities and the Dynamic Effects of a Shock to Monetary Policy. *Journal of Political Economy*, 113(1):1–45, February 2005. 4

R. De Haas and A. A. Popov. Finance and carbon emissions. *ECB Working Paper*, 2019. 25

C. Di Maria and S. Valente. Hicks meets hotelling: the direction of technical change in capital–resource economies. *Environment and Development Economics*, 13(6):691–717, 2008. 5

S. Dietz and N. Stern. Endogenous growth, convexity of damage and climate risk: how nordhaus' framework supports deep cuts in carbon emissions. *The Economic Journal*, 125 (583):574–620, 2015. 3, 24, 43

S. Dietz and F. Venmans. Cumulative carbon emissions and economic policy: in search of general principles. *Journal of Environmental Economics and Management*, 96:108–129, 2019. 4, 6, 10, 24, 29

S. Dietz, J. Rising, T. Stoerk, and G. Wagner. Economic impacts of tipping points in the climate system. *Proceedings of the National Academy of Sciences*, 118(34), 2021. 28

F. Diluiso, B. Annicchiarico, M. Kalkuhl, and J. C. Minx. Climate actions and macro-financial stability: The role of central banks. *Journal of Environmental Economics and Management*, 110:102548, 2021. 3, 4

Y. Dissou and L. Karnizova. Emissions cap or emissions tax? a multi-sector business cycle analysis. *Journal of Environmental Economics and Management*, 79:169–188, 2016. 4

T. Doh, G. Cao, and D. Molling. Should monetary policy monitor risk premiums in financial markets? *Federal Reserve Bank of Kansas City: Economic Review*, 100(1):7–30, 2015. 19

D. Duffie and K. J. Singleton. Simulated moments estimation of markov models of asset prices. *Econometrica: Journal of the Econometric Society*, pages 929–952, 1993. 23

T. Ehlers, B. Mojon, and F. Packer. Green bonds and carbon emissions: exploring the case for a rating system at the firm level. *BIS Quarterly Review, September*, 2020. 31

E. Escrig-Olmedo, M. Á. Fernández-Izquierdo, I. Ferrero-Ferrero, J. M. Rivera-Lirio, and M. J. Muñoz-Torres. Rating the raters: Evaluating how esg rating agencies integrate sustainability principles. *Sustainability*, 11(3):915, 2019. 20

I. Fender, M. McMorrow, V. Sahakyan, and O. Zulaica. Green bonds: the reserve management perspective. *BIS Quarterly Review*, September 2019. 25, 43

A. Ferrari and V. Nispi Landi. Whatever it takes to save the planet? central banks and unconventional green policy. *Central Banks and Unconventional Green Policy (February 15, 2021). Bank of Italy Temi di Discussione (Working Paper) No*, 1320, 2021. 4, 34

C. Fischer and M. Springborn. Emissions targets and the real business cycle: Intensity targets versus caps or taxes. *Journal of Environmental Economics and Management*, 62 (3):352–366, 2011. 4

C. Flammer. Corporate green bonds. *Journal of Financial Economics*, 2021. 26

J. Gali and T. Monacelli. Optimal monetary and fiscal policy in a currency union. *Journal of international economics*, 76(1):116–132, 2008. 64

M. Gertler and P. Karadi. A model of unconventional monetary policy. *Journal of Monetary Economics*, 58(1):17–34, January 2011. 4, 5, 6, 13, 20, 21, 22, 24, 25, 32

M. Golosov, J. Hassler, P. Krusell, and A. Tsyvinski. Optimal taxes on fossil fuel in general equilibrium. *Econometrica*, 82(1):41–88, 2014. 2, 3, 9, 10, 28

A. Grimaud and L. Rouge. Environment, directed technical change and economic policy. *Environmental and Resource Economics*, 41(4):439–463, 2008. 5

J. Hassler, P. Krusell, C. Olovsson, and M. Reiter. On the effectiveness of climate policies. *IIES Working Paper*, 2020. 2, 3

G. Heutel. How should environmental policy respond to business cycles? optimal policy under persistent productivity shocks. *Review of Economic Dynamics*, 15(2):244–264, 2012. 4, 6, 24

N. Jaimovich and S. Rebelo. Can news about the future drive the business cycle? *American Economic Review*, 99(4):1097–1118, 2009. 9

U. J. Jermann. Asset pricing in production economies. *Journal of monetary Economics*, 41 (2):257–275, 1998. 13, 23

L. S. Karp and C. P. Traeger. Prices versus quantities reassessed. *CESifo Working Paper*, 2018. 28

W. Nordhaus. A question of balance: Weighing the options on global warming policies. *Yale University Press, New Haven, CT*, 2008. 4, 6

W. D. Nordhaus. To slow or not to slow: the economics of the greenhouse effect. *The economic journal*, 101(407):920–937, 1991. 3

W. D. Nordhaus. Revisiting the social cost of carbon. *Proceedings of the National Academy of Sciences*, 114(7):1518–1523, 2017. 10

W. D. Nordhaus and A. Moffat. A survey of global impacts of climate change: replication, survey methods, and a statistical analysis. *NBER Working Paper*, 2017. 9, 24, 43

M. Pietrunti. Financial frictions and the real economy. *ESRB Working Paper Series*, 2017. 5, 14

A. Queralto. A model of slow recoveries from financial crises. *Journal of Monetary Economics*, 114:1–25, 2020. 9

L. Sager. Income inequality and carbon consumption: Evidence from environmental engel curves. *Energy Economics*, 84:104507, 2019. 2

S. Schmitt-Grohé and M. Uribe. Optimal simple and implementable monetary and fiscal rules. *Journal of monetary Economics*, 54(6):1702–1725, 2007. 69

K. Schubert. Macroeconomics and the environment. *Revue de l'OFCE*, (3):117–132, 2018. 4

F. Smets and R. Wouters. An Estimated Dynamic Stochastic General Equilibrium Model of the Euro Area. *Journal of the European Economic Association*, 1(5):1123–1175, September 2003. 4, 24, 25, 26, 68

S. Smulders and M. De Nooij. The impact of energy conservation on technology and economic growth. *Resource and Energy Economics*, 25(1):59–79, 2003. 5

N. Stern. The economics of climate change. *American Economic Review*, 98(2):1–37, 2008. 3, 24

J. B. Taylor. Discretion versus policy rules in practice. *Carnegie-Rochester Conference Series on Public Policy*, 39(1):195–214, December 1993. 15

C. P. Traeger. Uncertainty in the analytic climate economy. *CEPR Discussion Paper No. DP16065*, 2021. 29

I. B. Tucker. Microeconomics for today. *Cengage Learning*, 2010. 8

T. S. Van den Bremer and F. Van der Ploeg. The risk-adjusted carbon price. *American Economic Review*, 111(9):2782–2810, 2021. 29

R. Van der Ploeg, C. Hambel, and H. Kraft. Asset pricing and decarbonization: Diversification versus climate action. *University of Oxford Working Paper*, 2020. 3

M. L. Weitzman. A review of the stern review on the economics of climate change. *Journal of economic literature*, 45(3):703–724, 2007. 24

M. L. Weitzman. Ghg targets as insurance against catastrophic climate damages. *Journal of Public Economic Theory*, 14(2):221–244, 2012. 3, 24, 43

M. Woodford. Interest and prices. 2003. 4

A Appendix: Tables

TABLE 1
Calibrated parameter values (quarterly basis)

	Calibrated parameters	Values
Standard Macro Parameters		
σ	Risk aversion	2
$\varkappa$	% of Green firms in the economy	30
θ	Price elasticity	5
ξ	Price stickiness (Calvo parameter)	2/3
θ^P	Price stickiness (Rotemberg parameter)	$\frac{(\theta-1)\xi}{(1-\xi)(1-\xi\tilde{\beta})}$
$\bar{L}$	Labor supply	1/3

TABLE 2
Calibrated parameter values (quarterly basis)

	Calibrated parameters	Values
Environmental Parameters		
γ_d	CO_2 natural abatement	0.0021
$\theta_{1,g}$	Abatement cost parameter for sector G	0.02
$\theta_{2,g}$	Abatement cost parameter for sector G	2.7
$\theta_{1,b}$	Abatement cost parameter for sector B	0.05
$\theta_{2,b}$	Abatement cost parameter for sector B	2.7
υ_1^o	Temperature parameter	0.5
υ_2^o	Temperature parameter	0.00125
a	Damage function parameter	1.004
b	Damage function parameter	0.02

TABLE 3
Calibrated parameter values (quarterly basis)

	Calibrated parameters	Values
Banking Parameters		
Δ	Parameter impacting the discount factor of bankers	0.99
θ_B	Probability of staying a banker	0.98
ρ_c	Smoothing monetary rule coefficient	0.8
ϕ_y	Output policy parameter	0.2
ϕ_Π	Inflation policy parameter	1.5

TABLE 4
Estimated Parameters

		Estimation	
	Parameters	Mean	Standard Deviation
Standard Macro Parameters			
$\sigma_{A_{t,k}}$	Output shock standard deviation	0.0063361	7.2574e-06
$\rho_{A_{t,k}}$	Output shock persistence	0.76907	8.3156e-06
$\bar{g}/\bar{y}$	Public spending share in output	0.28503	1.9099e-05
η_i	Capital adjustment cost	1.7354	7.2439e-06
$1/(1+b/100)$	Discount factor	0.027254	6.4961e-06
$1+\gamma_Y/100$	Economy growth rate	0.21907	3.0773e-07
h	habits	0.22278	1.3859e-05
α	Capital intensity	0.34202	4.8802e-07
δ	Depreciation rate of capital	0.024995	1.5241e-07
θ_g	Price elasticity in sector G	11	6.1805e-06
θ_b	Price elasticity in sector B	7.0206	4.3802e-06
Environmental Parameters			
E^*	Rest of the world emissions	3.3666	3.0327e-06
φ_b	Emissions-to-output ratio in sector B	0.2849	1.5072e-06
Carbon Price	Carbon price level	0.0099078	4.5392e-06
Banking Parameters			
λ	Risk weight on loans	0.17618	5.9887e-06
ω	Proportional transfer to the entering bankers	0.006353	2.4101e-06

TABLE 5

Model moments compared to observed data (Euro Zone)

Target	Model	Data	Source
Macro Aggregates:			
Output Growth Volatility	0.0065	0.0066	Eurostat
Investment Growth Volatility	0.030	0.030	Eurostat
Consumption to output Growth Volatility	0.0047	0.0048	Eurostat
Mean Output Growth	0.0022	0.0023	Eurostat
Mean Investment Growth	0.0021	0.0023	Eurostat
Consumption to Output Ratio (%)	0.57	0.53	Eurostat
Government Spending to Output Ratio (%)	0.28	0.24	Eurostat
Marginal Cost of the Brown Sector (Normalized)	1	1	Chegut et al. [2019]
Marginal Cost of the Green Sector (6% higher than 'B')	1.06	1.06	Chegut et al. [2019]
Financial Aggregates:			
Risk-less Bond Mean Return (annualized)	1.07%	1.08%	ECB
Green Bonds Risk Premium (annualized)	0.80%	0.80%	Fender et al. [2019]
Brown Bonds Risk Premium (annualized)	0.80%	0.80%	Fender et al. [2019]
Banks' Capital Ratio (Equity as a % of RWA)	14.39%	14.40%	ECB
Environmental Aggregates:			
Global Level of Carbon Stock (GtC)	839	839	USDA
Emissions to Output Ratio (kCO_2 per $ of output)	0.21	0.21	Global Carbon Project/FRED
ETS Price (January 2021) in €	30	30	Bloomberg

TABLE 6

Sensitivity of the optimal carbon price to climate damages and dynamics

	Nordhaus		Dietz		Weitzman	
	$\upsilon_2^o = 0.00125$	$\upsilon_2^o = 0.0025$	$\upsilon_2^o = 0.00125$	$\upsilon_2^o = 0.0025$	$\upsilon_2^o = 0.00125$	$\upsilon_2^o = 0.0025$
Emissions Reduction (in%)	-	15%	5%	28%	15%	45%
Social Cost of Carbon (in €)	31.2	144.12	65.94	333.53	144.12	846.65
Temperature T^o (in Celsius)	1.06	2.07	1.05	2.04	1.03	2

Notes: The figures reported in the table show the sensitivity of the optimal price of carbon, temperature, and net-zero goal of 55 percent emissions reduction by 2030, to different levels of calibration of: i) the damage function (parameter "b"), and ii) the climate dynamics (parameter "υ_2^o"). With respect to the damage function, $b = 0.01$ corresponds to Nordhaus and Moffat [2017], $b = 0.02$ corresponds to Dietz and Stern [2015], and $b = 0.04$ corresponds to Weitzman [2012]. For the climate dynamics, $\upsilon_2^o = 0.00125$ corresponds to baseline case with $T^o < 1.1C$ by 2030, and $\upsilon_2^o = 0.0025$ corresponds to case with $T^o < 2.1C$ by 2030.

TABLE 7

Steady state values

	Optimal Policy	ETS Policy	ETS and Macropru		
			$\lambda_g = 0.75$	$\lambda_g = 0.5$	$\lambda_g = 0.25$
			$\lambda_b = 1.25$	$\lambda_b = 1.5$	$\lambda_b = 1.75$
	(1)	(2)	(3)	(4)	(5)
Consumption	1.2419	1.2372	1.2387	1.2402	1.2418
Aggregate Output	2.1139	2.1029	2.1019	2.1013	2.1011
Green Output	1.0937	1.0937	1.1012	1.1111	1.1213
Brown Output	1.06	1.0515	1.0425	1.0337	1.0251
Emissions to Output	0.2183	0.1569	0.1569	0.1569	0.1569
Green Sector Emissions	0.1034	0.0747	0.0754	0.0760	0.0767
Brown Sector Emissions	0.2876	0.2049	0.2032	0.2014	0.1998
Green Capital Stock	11.4318	11.3383	11.6359	11.9468	12.2717
Brown Capital Stock	10.4235	10.1552	9.9001	9.6554	9.4207
Green Real Rate	1.0045	1.0045	1.004	1.0035	1.003
Brown Real Rate	1.0045	1.0045	1.005	1.0055	1.006
ETS Price (in euros)	31.2	300	303	304	306
Carbon Cost as % of GDP in Green Sector	0.3278	0.5122	0.5122	0.5122	0.5122
Carbon Cost as % of GDP in Brown Sector	0.7650	1.4580	1.4580	1.4580	1.4580

Notes: The first column is the economy subject to an optimal carbon price. The second column is the economy subject to a carbon price consistent with the EU climate goals for 2030 (i.e. ETS cap net-zero objective), and the three last columns feature both a carbon price consistent with the EU climate goals for 2030 and an intervention of the macroprudential authority. We show how the economy responds to different risk-weight requirements related to climate risk exposure of firms. For instance the baseline scenario presents the case where an upgrade in the rating of the green bonds of the asset class BBB+ to A- and the downgrade in the rating of the brown bonds of the asset class BBB+ to BBB- (i.e. $\lambda_g = 0.75$ and $\lambda_b = 1.25$). The two other cases: i) with $\lambda_g = 0.5$ and $\lambda_b = 1.5$, and ii) with $\lambda_g = 0.25$ and $\lambda_b = 1.75$, represent a higher cut in the risk-weight associated with climate risk exposure (i.e. a higher upgrade and downgrade in the ratings).

TABLE 8

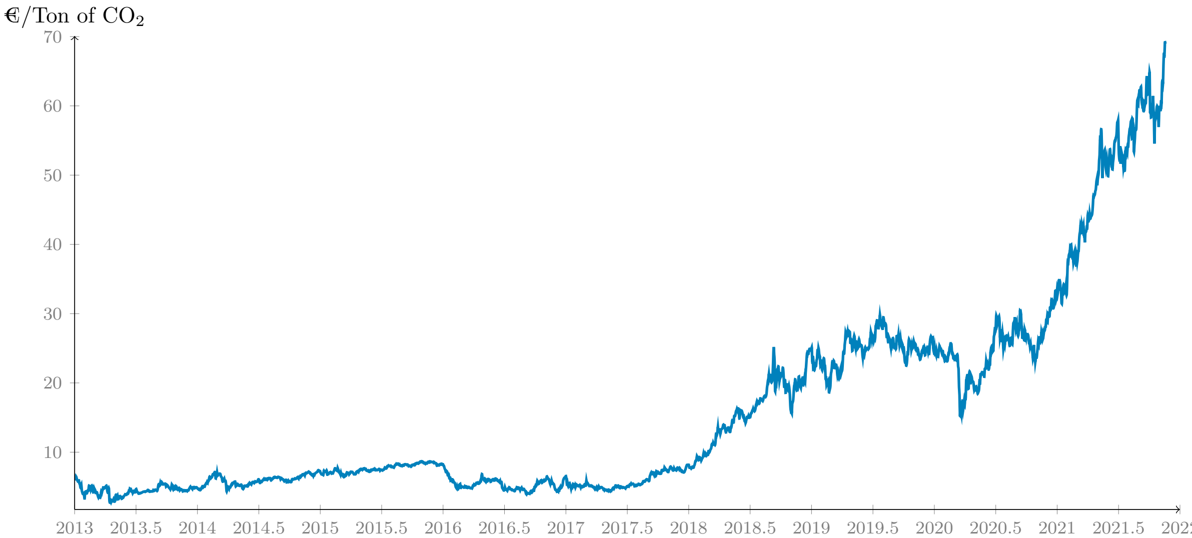
Risk premia volatility under the carbon price shock

	Baseline Model		**Model with QE Rules (ϕ_k^s=5)**	
	Mean	Standard Deviation	Mean	Standard Deviation
EP_g	0.1989	0.02	0.1989	0.0003
EP_b	0.1989	0.02	0.1989	0.0003
MC_g	0.9091	0.0001	0.9091	0.0003
MC_b	0.8571	0.0001	0.8571	0.0003
Q_g	1.0000	0.0002	1.0000	0.0001
Q_b	1.0000	0.0002	1.0000	0.0001
π_g	1.0000	0.0000	1.0000	0.0001
π_b	1.0000	0.0000	1.0000	0.0001

Notes: The figures reported in the table show the first and second moments of selected variables following a positive carbon price shock. The baseline model refers to the model with the ETS carbon price. The model with QE rules incorporates a reaction of the central bank to deviations in risk premia from their respective steady state.

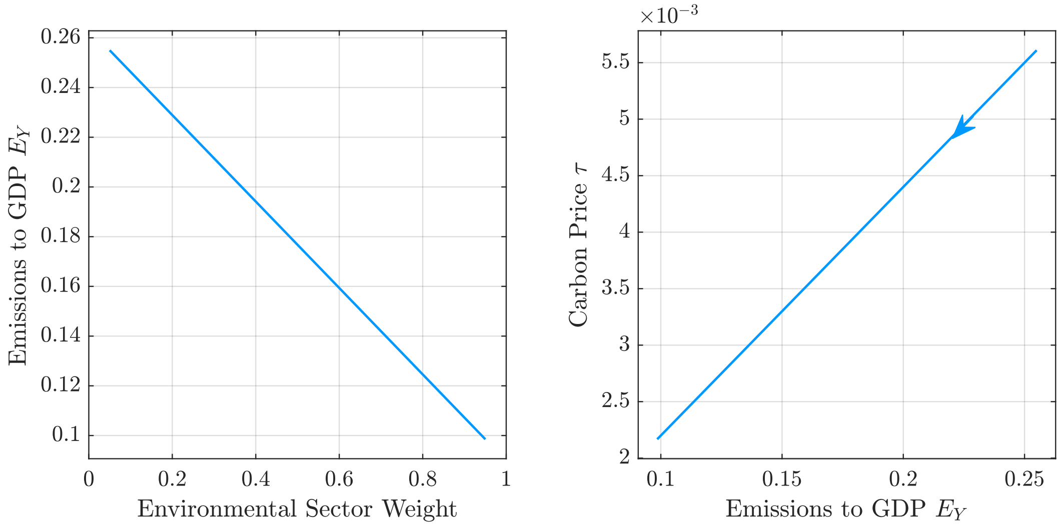
B Appendix: Figures

FIGURE 1. ETS Price in Euros per Ton of CO_2



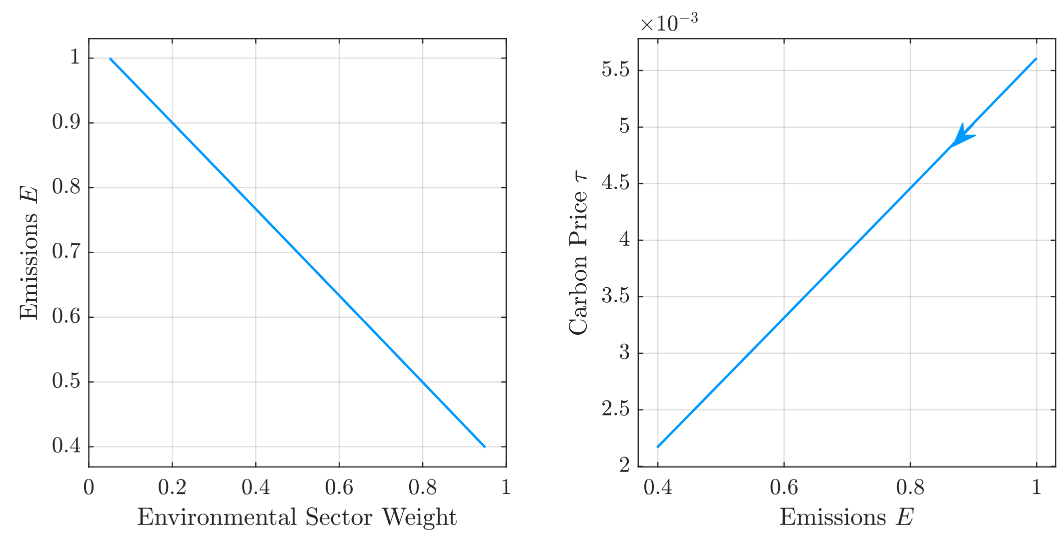
Notes: The figure displays the spot price of carbon permits traded within the ETS in euros per ton of CO_2. (Source: Bloomberg)

FIGURE 2. Share of the green sector, carbon intensity, and the environmental policy



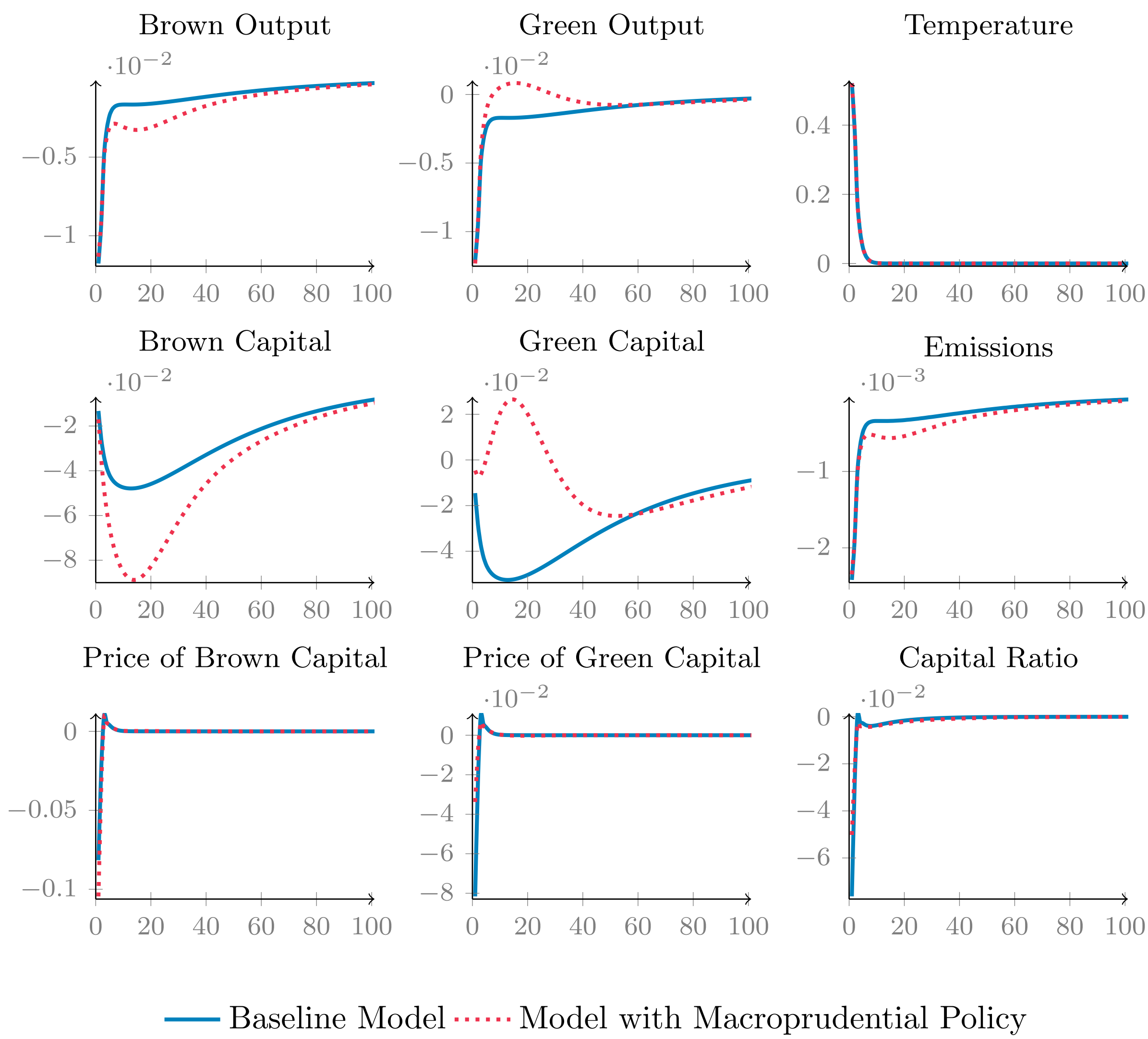
Notes: The graph on the left reports the interaction between emissions to output and the size of the green sector. The right graph reports how a change in the weight of the green sector drives the carbon price, through a decrease in the emissions to output ratio.

FIGURE 3. Share of the green sector, emission levels (normalized to one), and the environmental policy



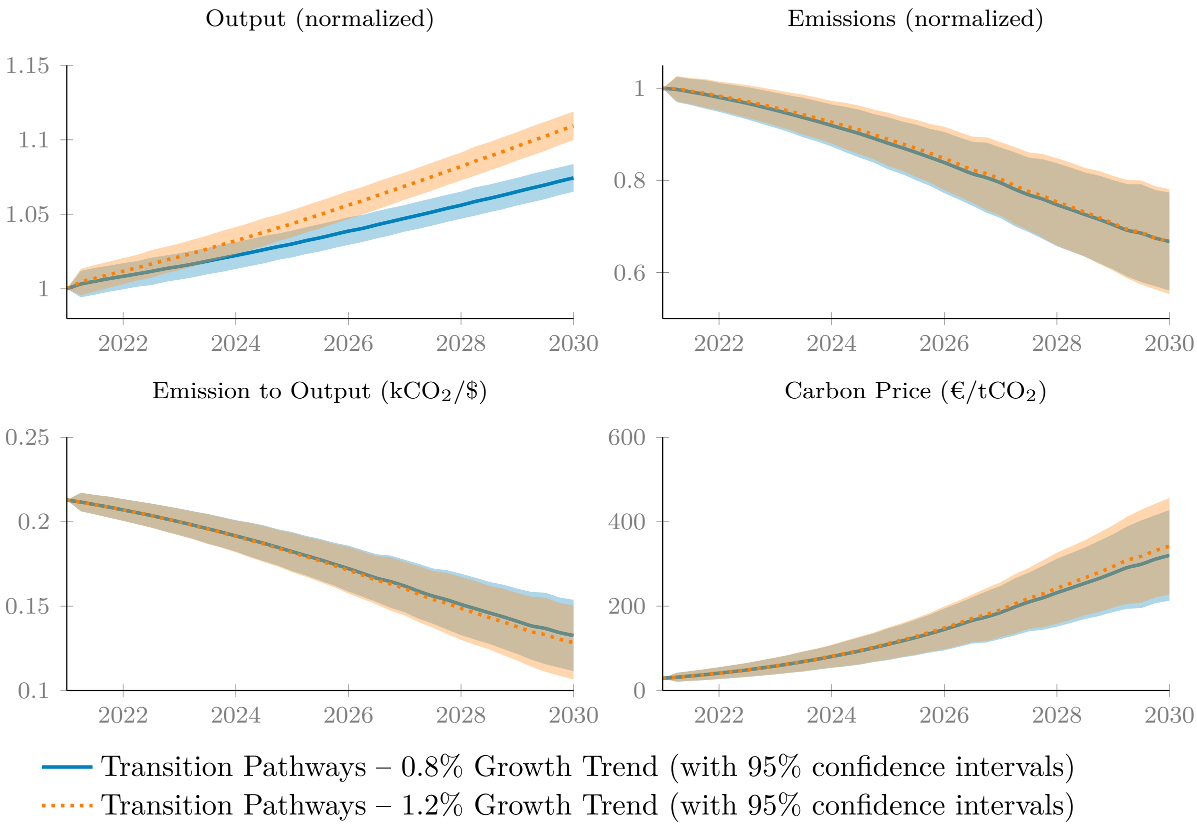
Notes: The graph on the left reports the interaction between emissions and the share of the green sector. The right graph reports how the share of the green sector shapes the carbon price.

FIGURE 4. Financial stability and climate risk



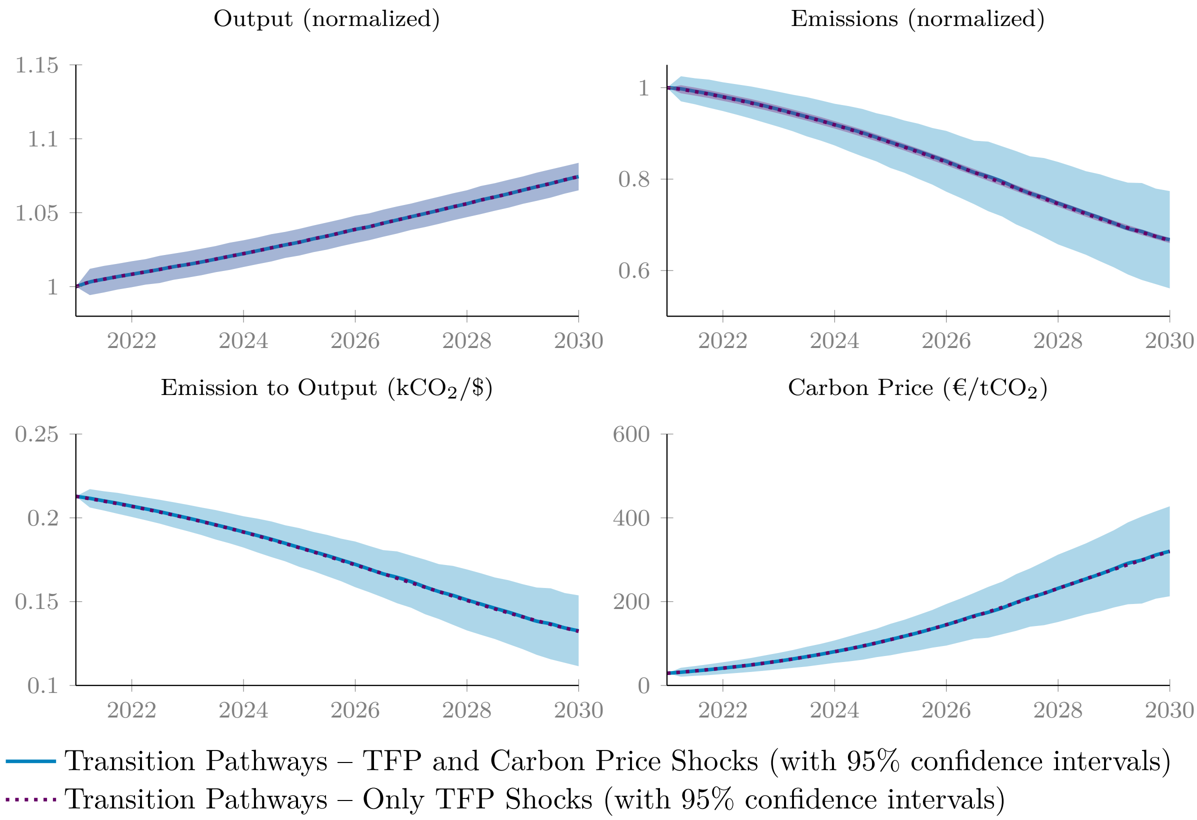
Notes: The figure shows the effect of a 0.5°C increase in the level of temperature, with and without macroprudential policy. In the baseline scenario, there is no sectoral macroprudential policy, which means $\lambda_b = \lambda_g = 1$. To illustrate the impact of green macroprudential policy on climate-related financial risk, we multiply/divide climate risk weights by a factor of 2, which means $\lambda_b = 2$ and $\lambda_g = 0.5$. Green macroprudential policy reduces the impact of a temperature increase on the global capital ratio by providing an incentive to banks to hold more green assets. The results are presented as percentage deviations from the steady state over quarterly periods.

FIGURE 5. Net-zero transition pathways with two different growth assumptions



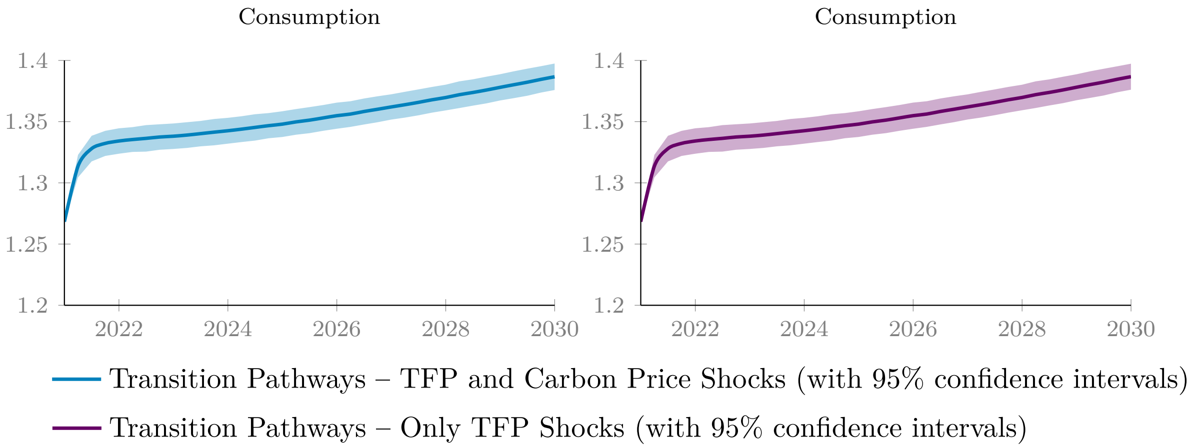
Notes: The figure reports the results of 2000 Monte Carlo simulation draws consistent with the net-zero target, according to two different growth scenarios. The blue line corresponds to the average per capita real growth over the last 20 years in the EZ (0.8%), while the orange dotted line corresponds to a more optimistic scenario in line with long term EZ trends (1.2%). The shaded blue and orange areas correspond to 95 percent confidence intervals for each scenario.

FIGURE 6. Net-zero transition pathways with and without carbon price uncertainty



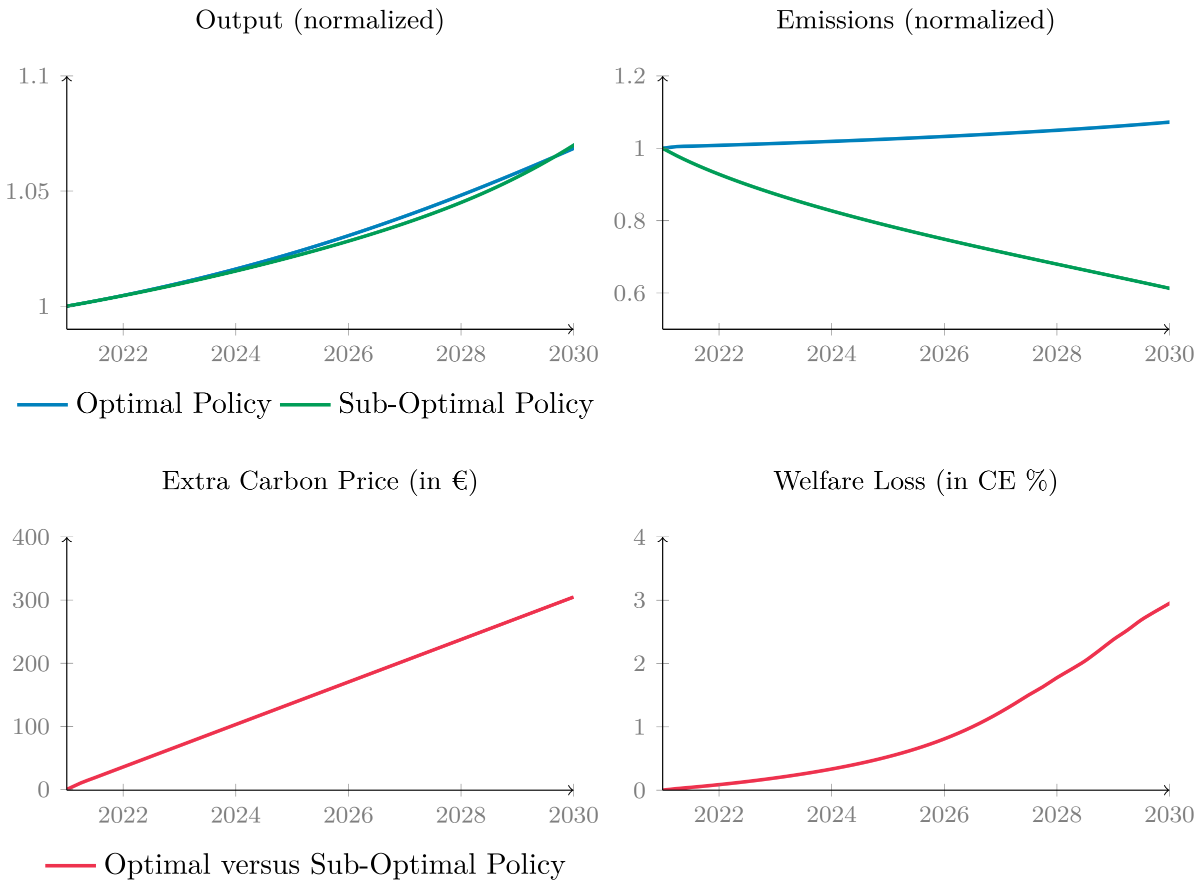
Notes: The figure reports the results of 2000 Monte Carlo simulation draws consistent with the net-zero target, according to the 0.8% growth scenario, where the carbon price is subject to carbon price volatility (i.e. carbon price shocks) and where the carbon price is not subject to carbon price volatility. The blue line corresponds to the average per capita real growth over the last 20 years in the EZ (0.8%) where the carbon price is subject to uncertainty, while the purple dotted line corresponds to the case where the carbon price is not subject to uncertainty. The shaded blue and purple areas correspond to the 95 percent confidence intervals for each scenario. Please note that for both scenarios output is subject to TFP shocks consistent with the past 20 years in the EZ.

FIGURE 7. Consumption pathways and carbon price uncertainty



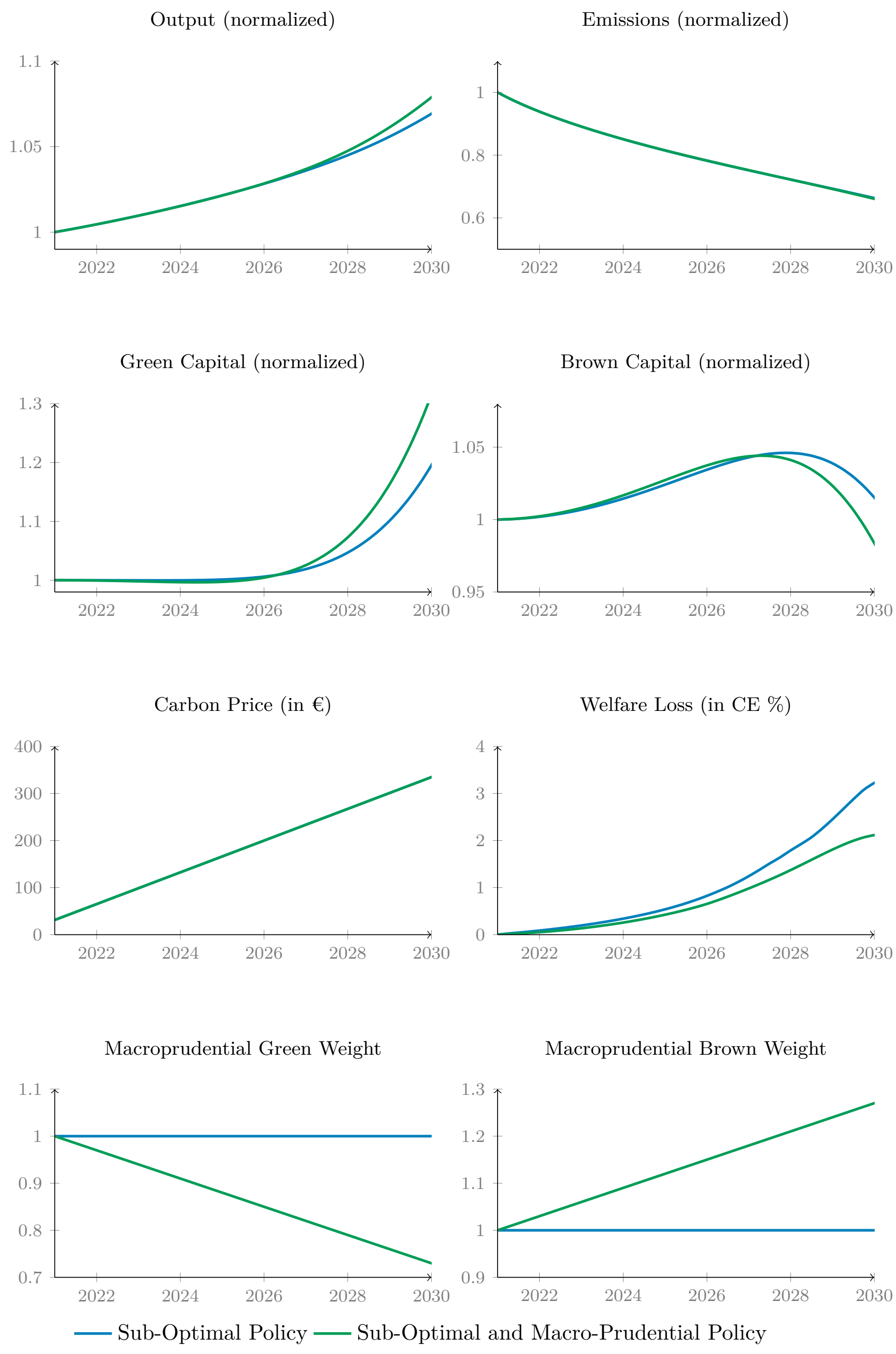
Notes: The figure reports the results of 2000 Monte Carlo simulation draws consistent with the net-zero target, according to the 0.8% growth scenario, where in one case the economy features carbon price volatility (i.e. carbon price shocks) and where in the other case the price of carbon is not subject to carbon price volatility. The blue line corresponds to the average per capita real growth over the last 20 years in the EZ (0.8%) where the carbon price is subject to uncertainty, while the purple line corresponds to the case where carbon price is not subject to uncertainty. The shaded blue and purple areas correspond to the 95 percent confidence intervals for each scenario. Please note that for both scenarios output is subject to TFP shocks consistent with the past 20 years in the EZ.

FIGURE 8. Transition pathways: optimal versus net-zero



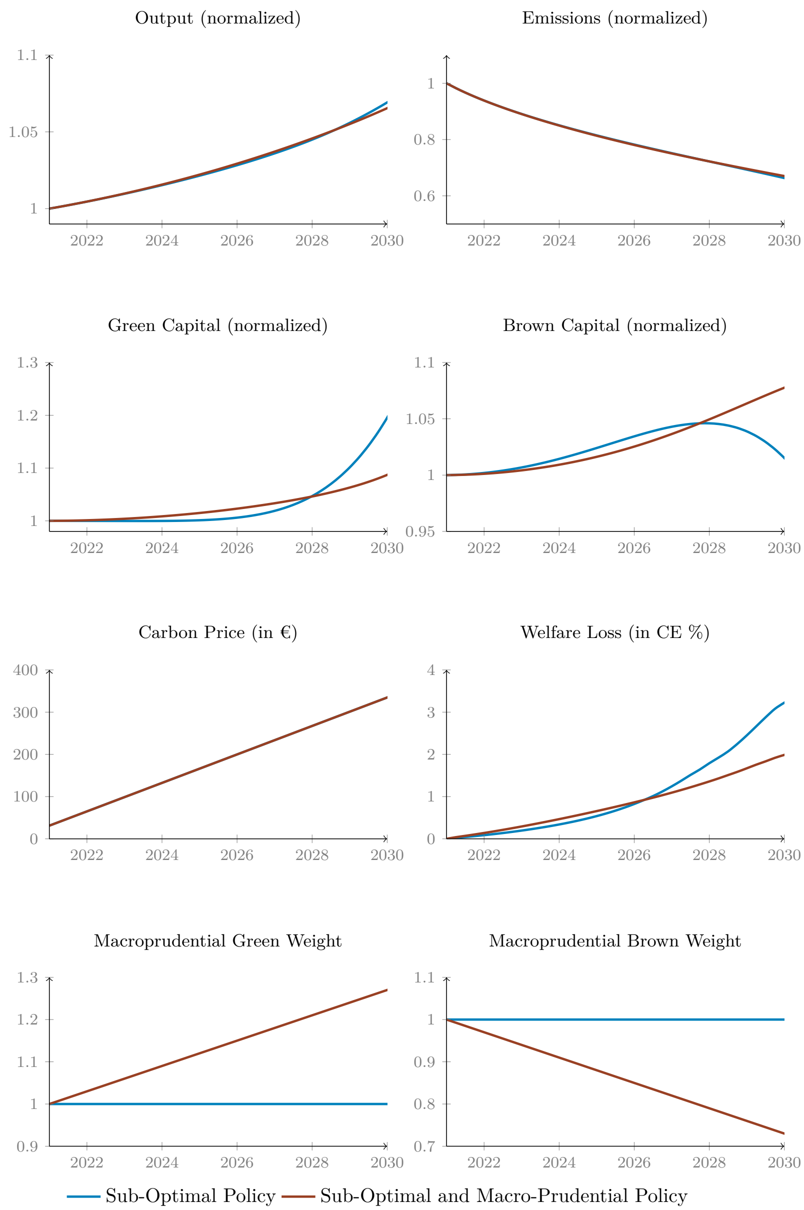
Notes: The figure compares the pathway consistent with the optimal carbon price (the social cost of carbon) to the net-zero ETS cap policy pathway. The blue line corresponds to the social planner choice, while the green dotted line corresponds to a pathway consistent with a reduction of emissions of 33 percent by 2030 (55 percent compared to 1990 level). The red lines show both the difference in carbon price and the welfare loss, between the optimal and sub-optimal policy (ETS inherent price). More specifically, the red graph on the left shows the trajectory of the extra carbon price, which is the carbon price consistent with the net-zero ETS cap policy minus the optimal price of the social planner. The graph on the right shows the welfare loss in consumption equivalent (CE), which is the difference between the welfare implied by the pathway of the social planner and the welfare implied by the pathway consistent with the net-zero objective.

FIGURE 9. Transition pathways (net-zero) with and without green macroprudential policy



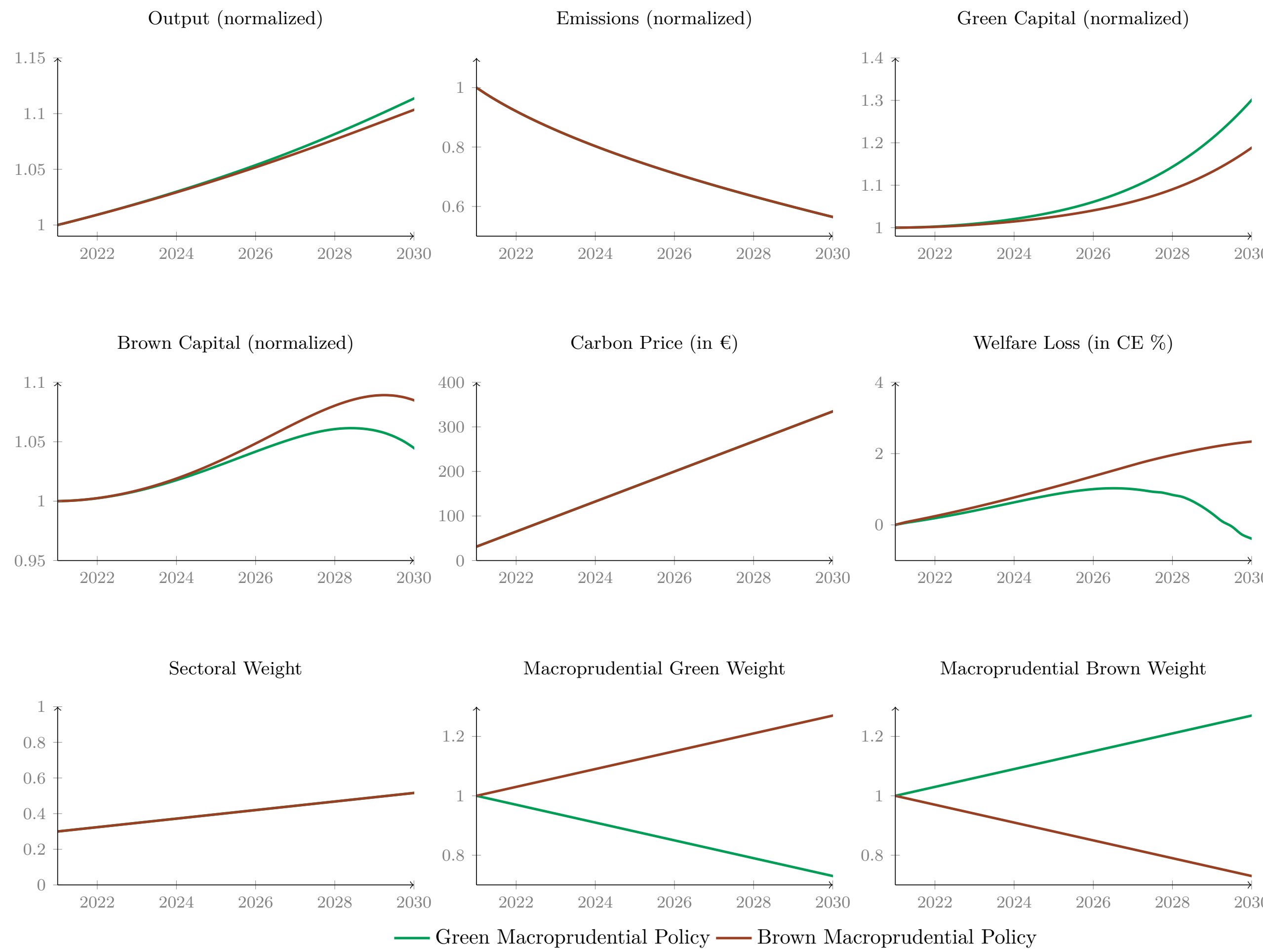
Notes: The figure compares a pathway consistent with the net-zero objective where a macroprudential policy takes into account climate risk and where it does not. The blue line corresponds to the case where no climate risk is considered ($\lambda_g = 1$ and $\lambda_b = 1$) and the green line corresponds to the case where the macroprudential authority considers climate risk with a progressive change in sectoral risk-weights ($\lambda_g \to 0.75$ and $\lambda_b \to 1.25$) .

FIGURE 10. Transition pathways (net-zero) with and without brown macroprudential policy



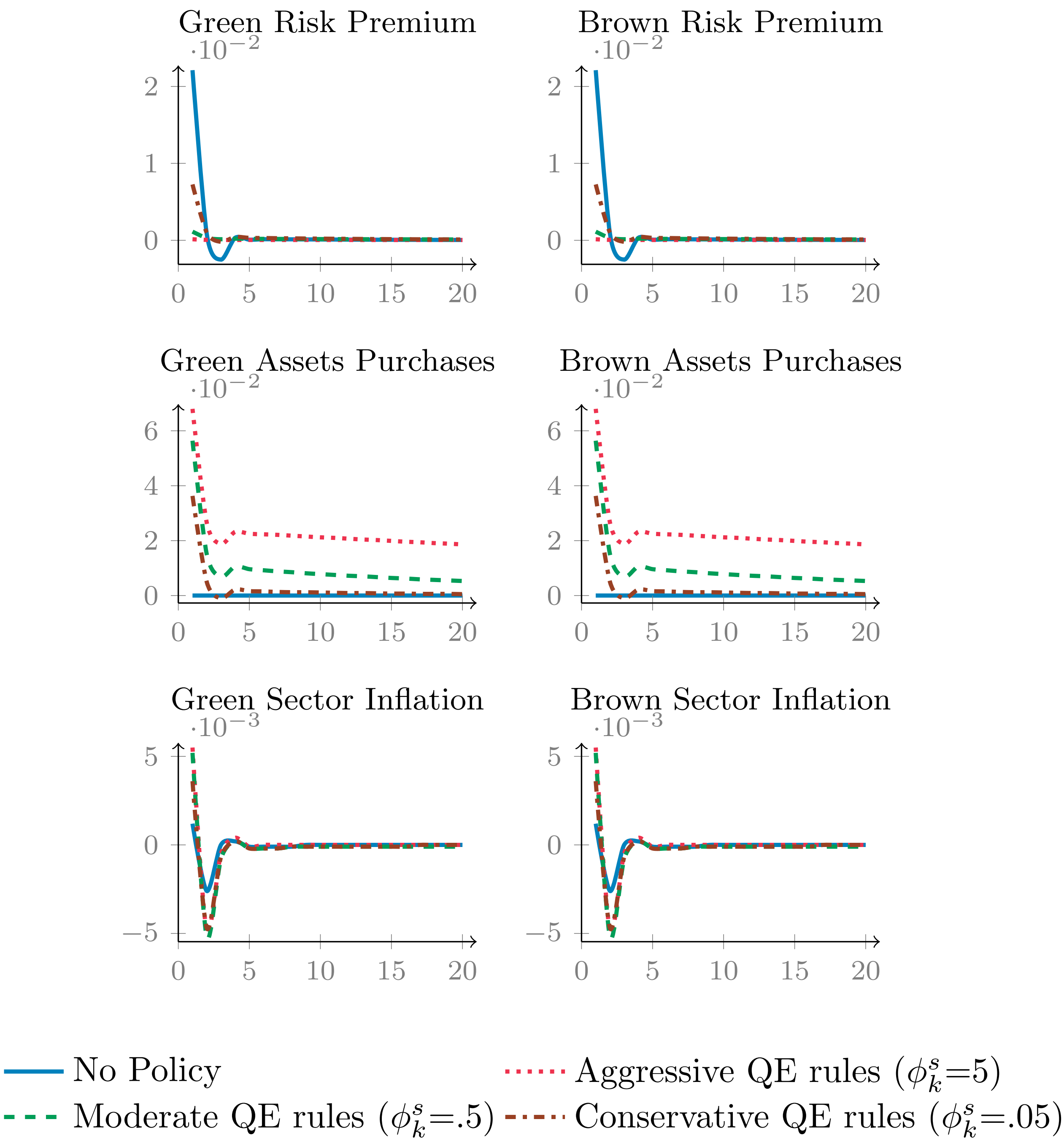
Notes: As a robustness exercise, we compare a pathway consistent with the net-zero objective where a macroprudential policy favors the brown sector over the green and where it stays neutral. The blue line corresponds to the neutral case ($\lambda_g = 1$ and $\lambda_b = 1$) and the brown line corresponds to the case where the macroprudential authority favors the brown sector ($\lambda_g \to 1.25$ and $\lambda_b \to 0.75$).

FIGURE 11. Transition pathways (net-zero) with macroprudential policy and an increase in the green sector share



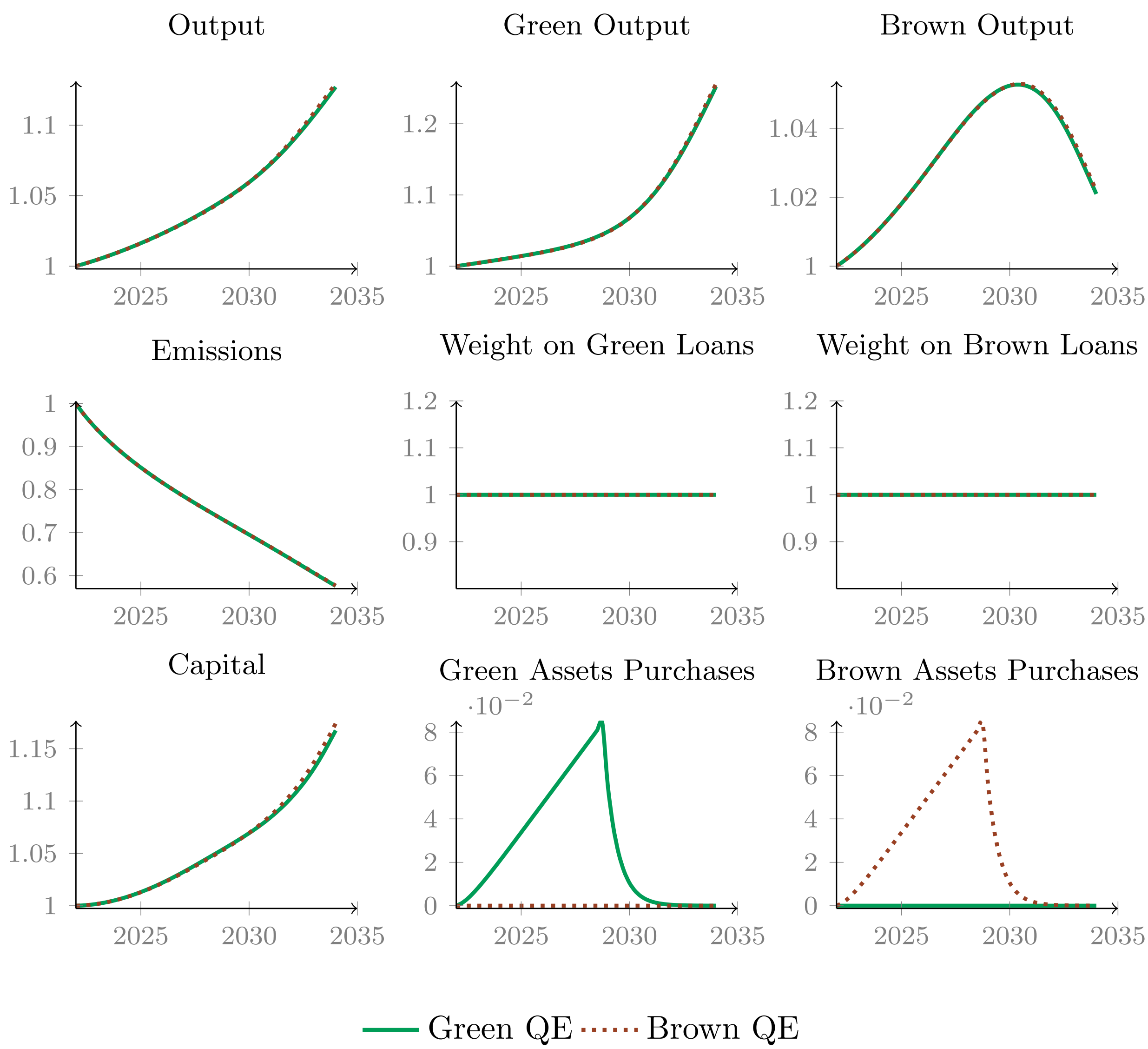
Notes: The figure compares a pathway consistent with the net-zero objective where the share of the green sector increases overtime ($\varkappa \rightarrow 50\%$) and where a macroprudential policy: i) takes into account climate risk, and ii) favors the brown sector over the green. The brown line corresponds to the case where the brown sector is favored over the green ($\lambda_g = 1.25$ and $\lambda_b = 0.75$) and the green line corresponds to the case where the macroprudential authority considers climate risk with a progressive change in sectoral risk-weights ($\lambda_g \rightarrow 0.75$ and $\lambda_b \rightarrow 1.25$) .

FIGURE 12. Responses to a positive carbon price shock (ε_t^τ). (The Rotemberg Case)



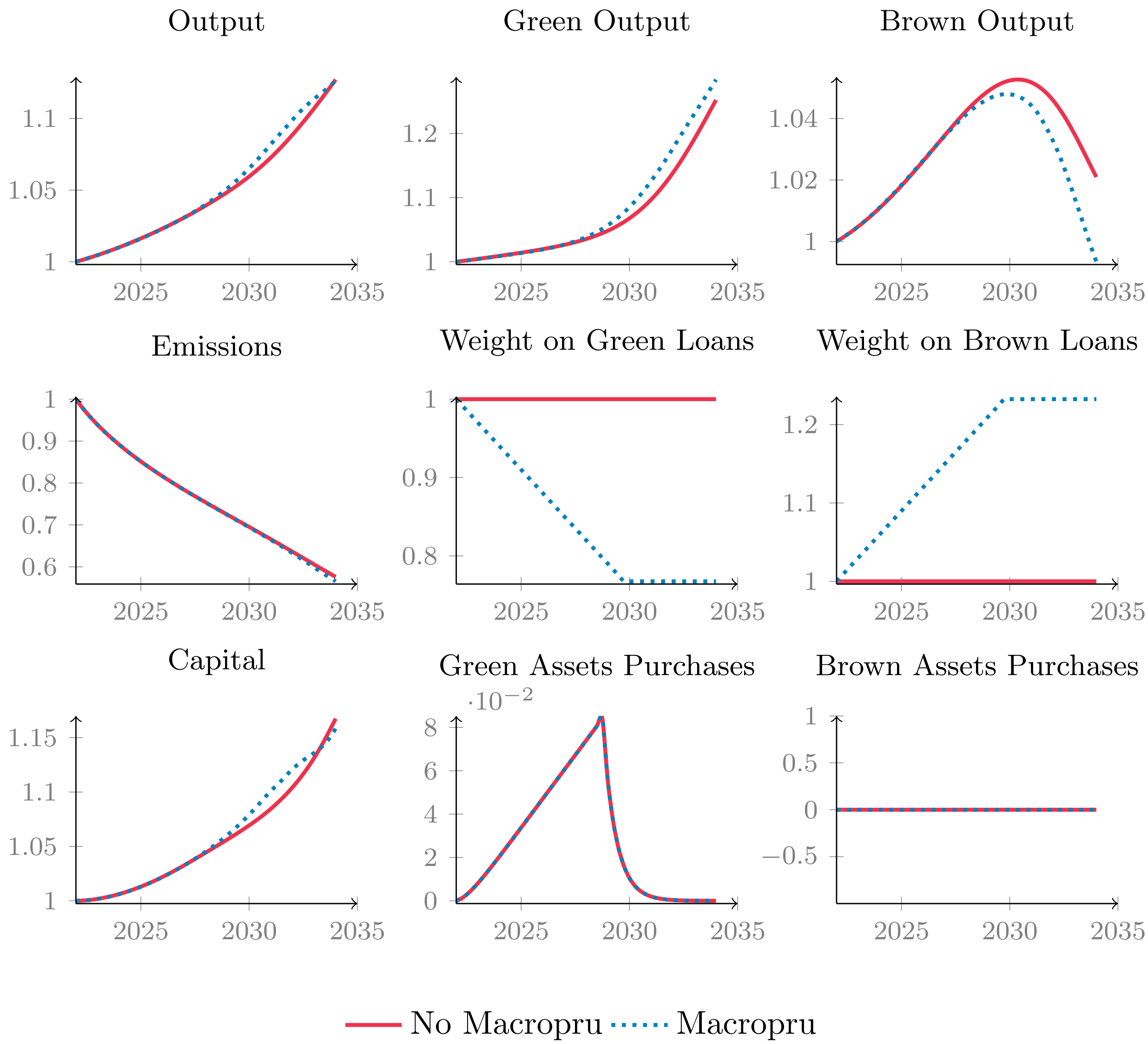
Notes: The figure shows the effect of a positive carbon price shock (ε_t^τ) calibrated on the ETS data on selected variables, with and without QE policy rules. The results are presented as percentage deviations from the steady state over quarterly periods.

FIGURE 13. Effect of transitory green and brown asset purchase programs



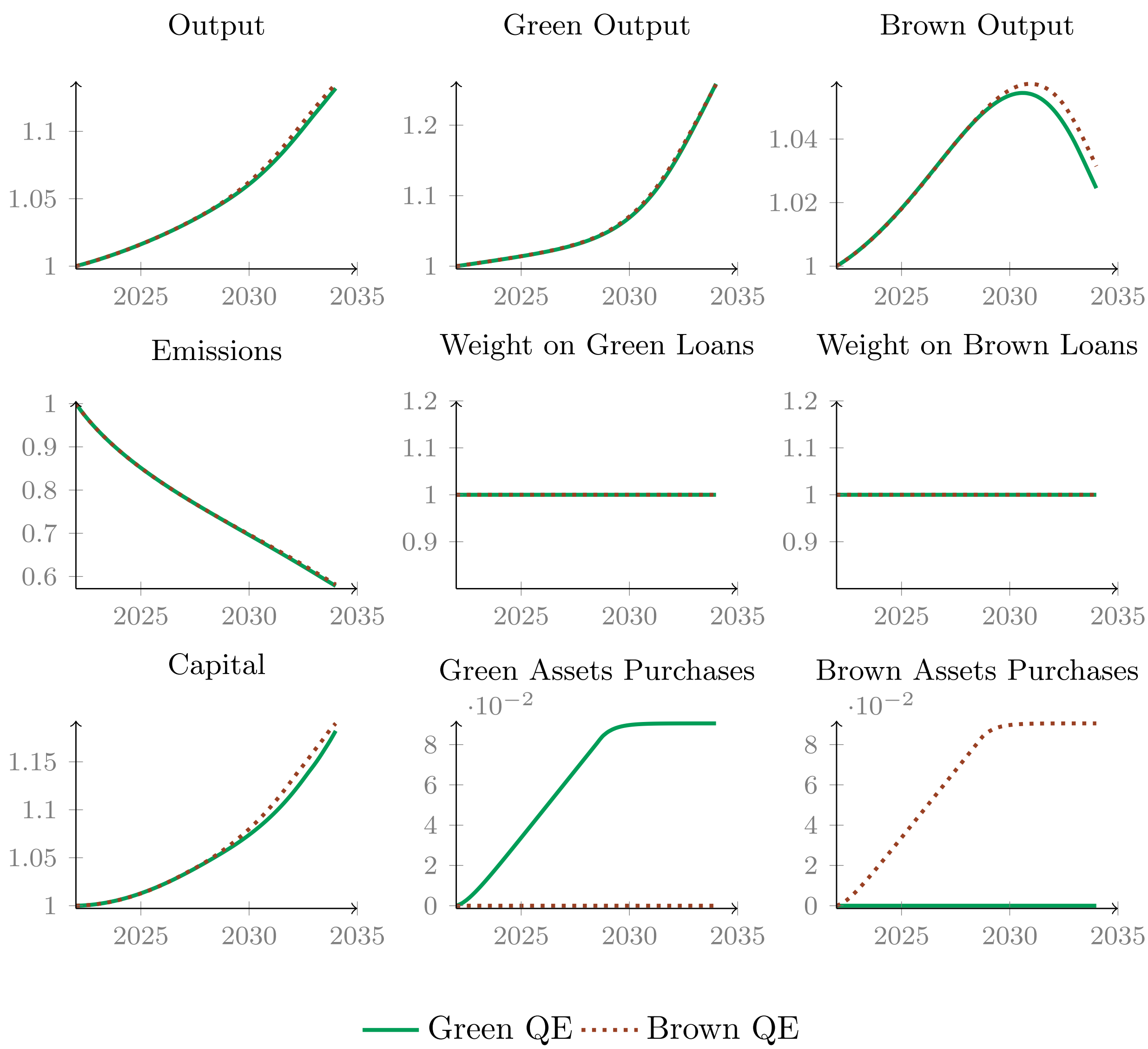
Notes: The figure shows the effect of transitory green and brown asset purchase programs (of about 9% of total asset in the economy) on a selection of variables, where the central bank stops purchasing bonds by 2028.

FIGURE 14. Effect of a transitory green asset purchase program with and without green macroprudential policy



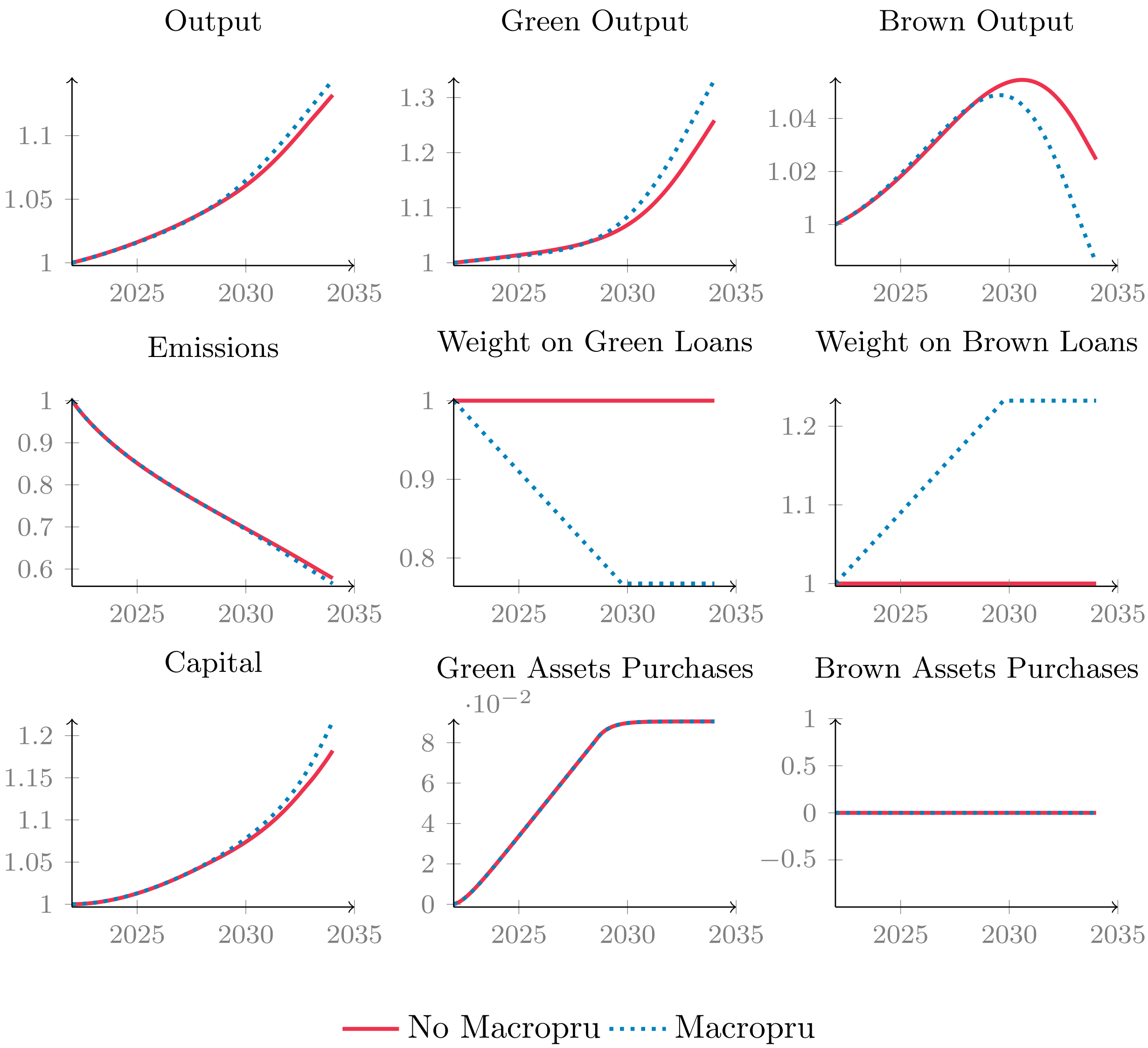
Notes: The figure shows the effect of transitory green asset purchase program (of about 9% of total asset in the economy) on a selection of variables, where the central bank stops purchasing bonds by 2028. In blue, the macroprudential authority sets a green macroprudential policy as presented in the previous section, while in red, it remains neutral.

FIGURE 15. Effect of permanent green and brown asset purchase programs



Notes: The figure shows the effect of permanent (where the central bank keeps the share of asset constant at about 9% of total assets in the economy) green and brown asset purchase programs on a selection of variables.

FIGURE 16. Effect of a permanent green asset purchase program with and without green macroprudential policy



<u>Notes:</u> The figure shows the effect of a permanent (where the central bank keeps the share of asset constant at about 9% of total assets in the economy) green asset purchase program on a selection of variables. In blue, the macroprudential authority sets a green macroprudential policy as presented in the previous section, while in red, it remains neutral.

(Online Appendix)

C Appendix: Climate Externality and Inefficiencies

C.1 The Social Planner Equilibrium: Centralized Economy

The benevolent social planner optimal allocation and optimal plan would choose to maximize welfare by choosing a sequence of allocations, for given initial conditions for the endogenous state variables, that satisfies the economy constraints.[46]

The planners' social problem for the households reads as follows:[47]

$$
\begin{aligned}
&\max E_t \sum_{t=0}^{\infty} \beta^t \Bigg(\frac{(C_t - hC_{t-1})^{1-\sigma}}{1-\sigma} \\
&+ \lambda_t \Bigg(\sum_k \Big(g(\varkappa) W_{t,k} L_{t,k} + \Pi_{t,k} \Big) + \Pi_t^T + T_t + R_t B_t - C_t - B_{t+1} \Bigg) \\
&+ \lambda_t \sum_k q_{t,k} \Bigg(\frac{P_{t,k}}{P_t} Y_{t,k} - W_{t,k} L_{t,k} - R^K_{t,k} K_{t,k} - f(\mu_{t,k}) Y_{t,k} - \Pi_{t,k} \Bigg) \\
&+ \lambda_t \sum_k \Psi_{t,k} (\varepsilon_t^{A,k} d(T_t^o) K_{t,k}^{\alpha} (\Gamma_t L_{t,k})^{1-\alpha} - Y_{t,k}) \\
&+ \lambda_t \varrho_t (E_t - \sum_k g(\varkappa) E_{t,k}) \\
&+ \lambda_t \S_t^X (X_t - \eta X_{t-1} - E_t) \\
&+ \lambda_t \S_t^T (T_t^o - \upsilon_1^o (\upsilon_2^o X_{t-1} - T_{t-1}^o) - T_{t-1}^o) \\
&+ \lambda_t \sum_k \S_{t,k}^E (E_{t,k} - (1 - \mu_{t,k}) \varphi_k Y_{t,k}) \Bigg)
\end{aligned}
$$

where as we will show below the Social Cost of Carbon SCC_t is the shadow value with respect to the temperature damages $\S_t^t$. $\Psi_{t,k}$ is the marginal cost component related to the firm's choice of labour and capital.

The first order conditions determining the SCC_t are the ones with respect to T_t^o, X_t, while the FOCs with respect to $E_{t,k}, \mu_{t,k}$ and $\Pi_{t,k}$ determine the level of abatement needed:

[46] This equilibrium will provide a benchmark solution, which we use to compare with the allocation obtained in the decentralized economy for the carbon policy.

[47] The social planner optimizes in an economy without price/financial frictions. This frictionless economy is the bare-bone model. In the following section, we present the decentralized economy, where we include financial and price frictions.

$$\lambda_t \S_t^T = E_t\beta(1-\upsilon_1^o)\lambda_{t+1}\S_{t+1}^T - \lambda_t \sum_k \Psi_{t,k}\varepsilon_t^{A,k}\frac{\partial d(T_t^o)}{\partial T_t^o}K_{t,k}^{\alpha}(\Gamma_t L_{t,k})^{1-\alpha} \tag{58}$$

$$\lambda_t \S_t^X = E_t\beta(\upsilon_1^o\upsilon_2^o)\lambda_{t+1}\S_{t+1}^T + E_t\beta\eta\lambda_{t+1}\S_{t+1}^X \tag{59}$$

$$\lambda_t \S_{t,k}^E = g(\varkappa)\lambda_t \S_t^X \tag{60}$$

$$\lambda_t q_{t,k} f'(\mu_{t,k}) = \varphi_k \lambda_t \S_{t,k}^E \tag{61}$$

$$\lambda_t = \lambda_t q_{t,k}. \tag{62}$$

Rearranging these FOCs we obtain the following SCC_t and abatement level:

$$\S_t^T = E_t(1-\upsilon_1^o)\Lambda_{t,t+1}\S_{t+1}^T - \sum_k \Psi_{t,k}\varepsilon_t^{A,k}\frac{\partial d(T_t^o)}{\partial T_t^o}K_{t,k}^{\alpha}(\Gamma_t L_{t,k})^{1-\alpha} \tag{63}$$

$$\S_t^X = E_t(\upsilon_1^o\upsilon_2^o)\Lambda_{t,t+1}\S_{t+1}^T + E_t\eta\Lambda_{t,t+1}\S_{t+1}^X \tag{64}$$

$$\S_{t,k}^E = g(\varkappa)\S_t^X \tag{65}$$

$$f'(\mu_{t,k}) = \varphi_k \S_{t,k}^E \tag{66}$$

C.2 The Decentralized Economy

The competitive equilibrium problem for the firms reads as follows:

$$\max E_t \sum_{i=0}^{\infty}\Bigg(\Bigg(\frac{P_{t,k}}{P_t}Y_{t,k} - W_{t,k}L_{t,k} - R_{t,k}^K K_{t,k} - f(\mu_{t,k})Y_{t,k} - \tau_{et,k}E_{t,k} - \Pi_{t,k}\Bigg)$$
$$+ \lambda_t\Psi_{t,k}(\varepsilon_t^{A,k}d(T_t^o)K_{t,k}^{\alpha}(\Gamma_t L_{t,k})^{1-\alpha} - Y_{t,k})$$
$$+ \lambda_t\Psi_{t,k}^E(E_{t,k} - (1-\mu_{t,k})\varphi_k Y_{t,k})\Bigg)$$

The first order conditions determining the environmental policy $\tau_{et,k}$ are the ones with respect to $E_{t,k}$ and $\mu_{t,k}$:

$$\Psi_t^E = \tau_{et,k} \tag{67}$$

$$f'(\mu_{t,k}) = \Psi_t^E \varphi_{t,k} \tag{68}$$

Thus, from both the household and firm FOCs, we get[48]:

$$\Psi^E_{t,k} = \tau_{et,k} \tag{69}$$
$$\Psi^E_{t,k} = \S^E_{t,k} \tag{70}$$
$$f'(\mu_{t,k}) = \S^E_{t,k}\varphi_k \tag{71}$$
$$\S^T_t = (1-\upsilon^o_1)\Lambda_{t,t+1}\S^T_{t+1} - \sum_k \Psi_{t,k}\varepsilon^{A,k}_t \frac{\partial d(T^o_t)}{\partial T^o_t} K^\alpha_{t,k}(\Gamma_t L_{t,k})^{1-\alpha} \tag{72}$$
$$\S^X_t = (\upsilon^o_1\upsilon^o_2)\Lambda_{t,t+1}\S^T_{t+1} + \eta\Lambda_{t,t+1}\S^X_{t+1} \tag{73}$$
$$\S^E_{t,k} = g(\varkappa)\S^X_t \tag{74}$$

The competitive equilibrium problem for the capital producing firms and financial intermediaries remains the same as the one presented in the financial intermediaries section. In the next section we present the Calvo problem for price frictions.[49]

C.3 The New Keynesian Phillips Curve à la Calvo

When monopolistic firms engage in infrequent price setting à la Calvo, we assume that intermediate goods producers for each sector re-optimize their prices $P_{jt,k}$ only when a price change signal is received. The probability (density) of receiving such a signal h periods from today is assumed to be independent from the last time the firm received the signal. A number of firms ξ will receive the price-change signal per unit of time. All other firms keep their old prices. Thus, the profit maximization of our intermediate firms reads as follows:

$$\max_{P_{jt,k}} \mathbb{E}_t \sum_{i=0}^{\infty} \xi^i \beta^i \Lambda_{t,t+i} \Pi_{jt+i,k} \tag{75}$$

$$\text{s.t. } Y_{jt,k} = \left(\frac{P_{jt,k}}{P_{t,k}}\right)^{-\theta_k} \left(\frac{P_{t,k}}{P_t}\right)^{-\theta} Y_t,$$
$$\text{and, } Y_{jt,k} = d(T^o_t)\varepsilon^{A_k}_t K^\alpha_{jt,k} L^{1-\alpha}_{jt,k}.$$

where $\beta^i\Lambda_{t,t+i} = \beta^i \frac{\varrho_{t+i}}{\varrho_t}$ is the real stochastic discount factor as in the Rotemberg case.

[48]Since $q_{t,k} = 1$ (as showed above), we retrieve that the input shadow cost $\Psi^E_{t,k}$ in the firms optimization problem is equal to $\S^E_{t,k}$.

[49]The Rotemberg case is presented in the core text.

The NK Philips Curve pricing equations are as follows:

$$p^*_{t,k} = \frac{P^*_{t,k}}{P_t} = \frac{\theta_k}{\theta_k - 1} \frac{\mathbb{E}_t \sum_{i=0}^{\infty} \xi^i \beta^i \Lambda_{t,t+i} \mathrm{MC}_{t+i,k} \Im_{t+i,k}}{\mathbb{E}_t \sum_{i=0}^{\infty} \xi^i \beta^i \Lambda_{t,t+i} \Im_{t+i,k}}, \tag{76}$$

where

$$\begin{aligned}
\Im_{t+i,k} &= \left(\frac{1}{P_{t+i,k}}\right)^{-\theta_k} \left(\frac{P_{t+i,k}}{P_{t+i}}\right)^{-\theta} P_t^{\theta} Y_{t+i} \\
&= {P_{t+i,k}}^{\theta_k - \theta} \left(\frac{P_{t+i}}{P_t}\right)^{\theta} Y_{t+i},
\end{aligned} \tag{77}$$

or equivalently:

$$\begin{aligned}
& p^*_{t,k} = \frac{P^*_{t,k}}{P_t} = \frac{\theta_k}{\theta_k - 1} \frac{S_{t,k} + \Upsilon_{t,k}}{\Theta_{t,k}}, \qquad (78) \\
& \text{with: } S_{t,k} = P_{t,k}^{\theta_k - \theta} \Psi_{t,k} Y_t + \frac{\varrho_{t+1}}{\varrho_t} \xi \beta \mathbb{E}_t \pi_{t+1}^{\theta} S_{t+1,k}, \\
& \text{and: } \Theta_{t,k} = P_{t,k}^{\theta_k - \theta} Y_t + \frac{\varrho_{t+1}}{\varrho_t} \xi \beta \mathbb{E}_t \pi_{t+1}^{\theta - 1} \Theta_{t+1,k}, \\
& \text{and: } \Upsilon_{t,k} = P_{t,k}^{\theta_k - \theta} \left[\theta_{1,k} \mu_{t,k}^{\theta_{2,k}} + \tau_{et,k}(1 - \mu_{t,k}) \varphi_k\right] Y_t + \frac{\varrho_{t+1}}{\varrho_k} \xi \beta \mathbb{E}_t \pi_{t+1}^{\theta} \Upsilon_{t+1,k},
\end{aligned}$$

with inflation $\pi_t = P_t / P_{t-1}$.

The optimal pricing condition p^* is obtained by equating the dynamic marginal revenues to the dynamic marginal costs. As in each period a fraction ξ of the intermediate firms of each sector choose their optimal price P^*_k, we can rewrite the final firms goods price P_k as a weighted average of the last period's price level and the price set by firms adjusting in the current period: $P_{t,k} = (\xi P_{t-1,k}^{1-\theta_k} + (1-\xi) P_{t,k}^{*1-\theta_k})^{\frac{1}{1-\theta_k}}$. In addition, please note that the j-index referring to our intermediate firms collapses as all firms for each sector, which are capable of setting their price optimally at t, will make the same decisions.

As presented in Gali and Monacelli [2008], the Calvo price dispersion $D_{pt,k}$ is essentially a measure of distortion introduced by dispersion in relative prices. Price dispersion is bounded below at 1, where 1 would be the value in the case of flexible prices. Price dispersion in our two-sector economy reads as:

$$\int_0^1 Y_{jt,k} \mathrm{dj} = \int_0^1 \left(\frac{P_{jt,k}}{P_{t,k}}\right)^{-\theta_k} \left(\frac{P_{t,k}}{P_t}\right)^{-\theta} Y_{t,k} \mathrm{dj} = D_{pt,k} Y_{t,k}, \tag{79}$$

with $D_{pt,k}$ the aggregate loss of efficiency induced by price dispersion of the intermediate goods. In other words, it also reads as $D_{pt,k} = (1-\xi)\left(\frac{P_{t,k}}{P_t}\right)^{(\theta_k-\theta)}\left(p^*_{t,k}\right)^{-\theta_k} + \xi\left(\frac{P_{t,k}}{P_t}\right)^{-\theta}\pi_{t,k}^{\theta_k}D_{pt-1,k}$.

Furthermore, as outlined in Annicchiarico and Di Dio [2015], our two-sector environmental components are impacted by the price dispersion as following:[50]

$$E_{t,k} = (1-\mu_{t,k})\varphi_k D_{pt,k}Y_{t,k}, \tag{80}$$

$$Z_{t,k} = \theta_{1,k}\mu_{t,k}^{\theta_{2,k}}D_{pt,k}Y_{t,k}. \tag{81}$$

C.4 The Non-Stationnary Equilibrium Conditions

The following equations represent the model equilibrium conditions.

Households:

$$\varrho_t = (C_t - hC_{t-1})^{-\sigma} - \beta h E_t\left\{(C_{t+1}-hC_t)^{-\sigma}\right\}, \tag{82}$$

$$1 = \beta E_t \Lambda_{t,t+1}R_{t+1}, \tag{83}$$

Final firms:

$$Y_t = \left(\varkappa^{\frac{1}{\theta}}Y_{t,g}^{1-\frac{1}{\theta}} + (1-\varkappa)^{\frac{1}{\theta}}Y_{t,b}^{1-\frac{1}{\theta}}\right)^{\frac{1}{1-\frac{1}{\theta}}}, \tag{84}$$

[50] Note that, as in the canonical NK models, production and profits are also affected by the price dispersion $Y_{t,k} = d(T_t^o)\varepsilon_t^{A_k}K_{t,k}^{\alpha}L_t^{1-\alpha}D_{pt,k}^{-1}$ and $\Pi_{t,k} = (1-MC_{t,k}D_{pt,k})Y_{t,k}$.

Intermediate firms:

$$Y_{t,k} = d(T_t^o)\varepsilon_t^{A_k} K_{t,k}^{\alpha} L_t^{1-\alpha} D_{pt,k}^{-1}, \tag{85}$$

$$T_t^o = \upsilon_1^o(\upsilon_2^o X_{t-1} - T_{t-1}^o) + T_{t-1}^o, \tag{86}$$

$$X_t = (1-\gamma_d)X_{t-1} + E_t + E_t^*, \tag{87}$$

$$E_{t,k} = (1-\mu_{t,k})\varphi_k D_{pt,k} Y_{t,k}, \tag{88}$$

$$Z_{t,k} = \theta_{1,k}\mu_{t,k}^{\theta_{2,k}} D_{pt,k} Y_{t,k}, \tag{89}$$

$$R_{t,k}^K = \alpha\Psi_{t,k}\frac{Y_{t,k}}{K_{t,k}}, \tag{90}$$

$$W_{t,k}^K = (1-\alpha)\Psi_{t,k}\frac{Y_{t,k}}{L_{t,k}}, \tag{91}$$

$$\tau_{et,k} = \frac{\theta_{1,k}\theta_{2,k}}{\varphi_k}\mu_{jt,k}^{\theta_{2,k}-1}, \tag{92}$$

$$MC_{t,k} = \Psi_{t,k} + \theta_{1,k}\mu_{t,k}^{\theta_{2,k}} + \tau_{et,k}(1-\mu_{t,k})\varphi_k, \tag{93}$$

New Phillips Curve equation (the Rotemberg case):

$$\theta^P \pi_{t,k}(\pi_{t,k}-1) = \left(\frac{P_{t,k}}{P_t}\right)^{-\theta}\left(\frac{P_{t,k}}{P_t}(1-\theta_k) + \theta_k MC_{t,k}\right) + E_t\left\{\beta\Lambda_{t,t+1}\frac{Y_{t+1}}{Y_t}\theta^P\pi_{t+1,k}(\pi_{t+1,k}-1)\right\} \tag{94}$$

New Phillips Curve equations (the Calvo case):

$$p_{t,k}^* = \frac{P_{t,k}^*}{P_t} = \frac{\theta_k}{\theta_k - 1}\frac{S_{t,k} + \Upsilon_{t,k}}{\Theta_{t,k}}, \tag{95}$$

$$S_{t,k} = P_{t,k}^{\theta_k-\theta}\Psi_{t,k}Y_t + \frac{\varrho_{t+1}}{\varrho_t}\xi\beta\mathbb{E}_t\pi_{t+1}^{\theta}S_{t+1,k}, \tag{96}$$

$$\Theta_{t,k} = P_{t,k}^{\theta_k-\theta}Y_t + \frac{\varrho_{t+1}}{\varrho_t}\xi\beta\mathbb{E}_t\pi_{t+1}^{\theta-1}\Theta_{t+1,k}, \tag{97}$$

$$\Upsilon_{t,k} = P_{t,k}^{\theta_k-\theta}\left[\theta_{1,k}\mu_{t,k}^{\theta_{2,k}} + \tau_{et,k}(1-\mu_{t,k})\varphi_k\right]Y_t + \frac{\varrho_{t+1}}{\varrho_t}\xi\beta\mathbb{E}_t\pi_{t+1}^{\theta}\Upsilon_{t+1,k}, \tag{98}$$

$$D_{pt,k} = (1-\xi)\left(\frac{P_{t,k}}{P_t}\right)^{(\theta_k-\theta)}\left(p_{t,k}^*\right)^{-\theta_k} + \xi\left(\frac{P_{t,k}}{P_t}\right)^{-\theta}\pi_{t,k}^{\theta_k}D_{pt-1,k}, \tag{99}$$

$$P_{t,k} = (\xi P_{t-1,k}^{1-\theta_k} + (1-\xi)P_{t,k}^{*1-\theta_k})^{\frac{1}{1-\theta_k}}, \tag{100}$$

Other NK equations:

$$\pi_t = P_t/P_{t-1}, \tag{101}$$

$$\pi_{t,g} = P_{t,g}/P_{t-1,g}, \tag{102}$$

$$\pi_{t,b} = P_{t,b}/P_{t-1,b}, \tag{103}$$

$$P_t = \left(\varkappa P_{t,g}^{1-\theta} + (1-\varkappa)P_{t,b}^{1-\theta}\right)^{\frac{1}{1-\theta}}, \tag{104}$$

$$\pi_t = \left(\varkappa \frac{P_{t,g}}{P_t}\pi_{t,g}^{\frac{\theta-1}{\theta}} + (1-\varkappa)\frac{P_{t,b}}{P_t}\pi_{t,b}^{\frac{\theta-1}{\theta}}\right), \tag{105}$$

Capital producing firms:

$$I_{t,k}^n = I_{t,k} - \delta K_{t,k}, \tag{106}$$

$$K_{t+1,k} = K_{t,k} + I_{t,k}^n, \tag{107}$$

$$f_k(.) = \frac{\eta_i}{2}\left(\frac{I_{t,k}}{I_{t-1,k}} - \theta^I\right)^2, \tag{108}$$

$$Q_{t,k} = 1 + f_k(.) + f_k'(.)\left(\frac{I_{t,k}}{I_{t-1,k}}\right) - \beta E_t\left\{\Lambda_{t,t+1}f_k'(.)\left(\frac{I_{t+1,k}}{I_{t,k}}\right)^2\right\}, \tag{109}$$

Financial Intermediaries:

$$Q_{t,g}S_{t,g} + Q_{t,b}S_{t,b} = N_t + B_t, \tag{110}$$

$$N_t = \theta_B[(R_{t,g} - R_t)Q_{t-1,g}S_{t-1,g} + (R_{t,b} - R_t)Q_{t-1,b}S_{t-1,b}] + (\theta_B R_t + \omega)N_{t-1}, \tag{111}$$

$$V_t = \lambda\nu_t(\lambda_g Q_{t,g}S_{t,g} + \lambda_d Q_{t,b}S_{t,b}) + \Delta\beta E_t\left\{\Lambda_{t,t+1}\Omega_{t+1}R_{t+1}N_t\right\}, \tag{112}$$

$$\Gamma_t^B N_t = \nu_t\Gamma_t^B N_t + \Delta\beta E_t\left\{\Lambda_{t,t+1}\Omega_{t+1}R_t N_t\right\}, \tag{113}$$

$$\Gamma_t^B = \frac{1}{1-\nu_t}\Delta\beta E_t\left\{\Lambda_{t,t+1}\Omega_{t+1}R_{t+1}\right\}, \tag{114}$$

$$\nu_t\lambda_k\lambda = \Delta\beta E_t\left\{\Lambda_{t,t+1}\Omega_{t+1}(R_{t+1,k} - R_{t+1})\right\}, \tag{115}$$

$$0 = \nu_t\left[\Gamma_t^B N_t - \lambda(\lambda_g Q_{t,g}S_{t,g} + \lambda_b Q_{t,b}S_{t,b})\right], \tag{116}$$

$$\mathrm{RP}_{t,k} = R_{t,k} - R_t, \tag{117}$$

Central Bank:[51]

$$i_t - \bar{\imath} = \rho_c \left(i_{t-1} - \bar{\imath}\right) + (1 - \rho_c) \left[\phi_\pi \left(\pi_t - \bar{\pi}\right) + \phi_y \left(y_t - y_{t-1}\right)\right], \tag{118}$$

$$i_t = R_t E_t \left\{\pi_{t+1}\right\}, \tag{119}$$

Government:

$$G_t = T_t + \tau_{et} E_t + RP_{t,g} \psi_{t,g} K_{t,g} + RP_{t,d} \psi_{t,b} K_{t,b}, \tag{120}$$

$$G_t = \frac{\bar{g}}{\bar{y}} Y_t, \tag{121}$$

Environmental Policy (when the policy is sub-optimal (E_t =cap)):

$$E_t = \text{Cap}_t, \tag{122}$$

$$\text{Cap}_t = \text{Cap}/\Gamma_t^{\text{Cap}}, \tag{123}$$

Environmental Policy (when the policy is optimal ($\tau_{et,k}$ =social cost of carbon)):

$$\tau_{et,k} = g(\varkappa)\text{SCC}_t, \tag{124}$$

$$\text{SCC}_t = \eta\beta \frac{\lambda_{t+1}}{\lambda_t} \text{SCC}_{t+1} + (\upsilon_1^o \upsilon_2^o)\beta \frac{\lambda_{t+1}}{\lambda_t} \S_{t+1}^T, \tag{125}$$

$$\S_t^T = (1 - \upsilon_1^o)\beta \frac{\lambda_{t+1}}{\lambda_t} \S_{t+1}^T - \sum_k \Psi_{t,k} \varepsilon_t^{A,k} \frac{\partial d(T_t^o)}{\partial T_t^o} K_{t,k}^\alpha (\Gamma_t L_{t,k})^{1-\alpha}, \tag{126}$$

Aggregate variables:

$$E_t = \sum_k g(\varkappa) E_{t,k}, \tag{127}$$

$$K_t = \sum_k g(\varkappa) K_{t,k}, \tag{128}$$

$$I_t = \sum_k g(\varkappa) I_{t,k}, \tag{129}$$

$$Z_t = \sum_k g(\varkappa) Z_{t,k}, \tag{130}$$

[51] To ensure stationarity over the BGP, the central bank sets its interest rates following the Taylor rule in the spirit of Smets and Wouters [2003].

Aggregate resource constraint (price stickiness à la Rotemberg):

$$Y_t = C_t + G_t + I_t + \sum_k g(\varkappa)[f_k(.)I_{t,k}] + \sum_k g(\varkappa)\Delta^P_{t,k} Y_t + Z_t. \tag{131}$$

Aggregate resource constraint (price stickiness à la Calvo):

$$Y_t = C_t + G_t + I_t + \sum_k g(\varkappa)[f_k(.)I_{t,k}] + Z_t. \tag{132}$$

C.5 Welfare Distortion

When $\tau_{et,k}$ moves away from $\tau^*_{et,k}$, losses in household lifetime consumption and welfare grow:

$$\Delta_{\{\tau-\tau^*\}}\text{Welfare} < 0,$$

As in Schmitt-Grohé and Uribe [2007], we define welfare under the optimal policy, conditional on the state of the economy in period $i = 0$ being the non-stochastic steady state associated with that regime and remaining under that regime forever, as $\text{Welfare}_t^{\tau^*}$. Similarly, Welfare_t^{τ} represents welfare under the sub-optimal policy:

$$\text{Welfare}_t^{\tau^*} = E_t \sum_{i=0}^{\infty} \beta^i U(C_t^{\tau^*}) \tag{133}$$

$$\text{Welfare}_t^{\tau} = E_t \sum_{i=0}^{\infty} \beta^i U(C_t^{\tau}) \tag{134}$$

where $C_t^{\tau^*}$ and C_t^{τ} denote the particular plans for consumption under the optimal regime and sub-optimal regime, respectively.

Now, let λ_W denote welfare costs associated with the sub-optimal fiscal policy in terms of consumption. It is defined as the fraction of the optimal consumption process that a household would be willing to give up to be as well off under the sub-optimal policy (τ) as under the optimal policy (τ^*).

$$\text{Welfare}_t^{\tau} = E_t \sum_{i=0}^{\infty} \beta^i U((1-\lambda_W)C_t^{\tau^*}) \tag{135}$$

As the utility function is a CRRA, no closed form solution exists to characterize the loss in welfare denoted λ_W. We perform a numerical exercise[52] to compute the unconditional λ_W.

We can reduce the problem to the following expression:[53]

$$\begin{aligned}\text{Wedge}_\text{C} = \left(\frac{(C_{t+i} - hC_{t+i-1})^{1-\sigma}}{1-\sigma} - \frac{(C^*_{t+i} - hC^*_{t+i-1})^{1-\sigma}}{1-\sigma}\right) &\propto \Delta C_t \\ &\propto \Delta Y_t - \Delta I_t - \Delta G_t - \Delta Z_t \\ &\propto \Delta(1-g)Y_t - \Delta I_t - \Delta Z_t\end{aligned}$$

Thus, the total effect on consumption reads as follows:

$$\text{Wedge}_\text{C} \propto (1-g)(Y_t - Y_t^*) - (I_t - I_t^*) - (Z_t - Z_t^*)$$

As argued above, and without a loss of generality, we can focus on one sector and draw the same conclusion for the model with both sectors:

$$\begin{aligned}\text{Wedge}_{\text{C}_k} \propto &(1-g)(\varepsilon_t^{A,k}\Gamma_t^{1-\alpha}\bar{L}^{1-\alpha})(d(T_t^o)K_{t,k}^\alpha - d(T_t^o)^* K_{t,k}^{\alpha\,*}) \\ &- (f(K_{t,k}) - f(K_{t,k})^*) \\ &- ((\varepsilon_t^{A,k}\Gamma_t^{1-\alpha}\bar{L}^{1-\alpha})(d(T_t^o)K_{t,k}^\alpha f(\mu_{t,k}) - d(T_t^o)^* K_{t,k}^{\alpha\,*} f(\mu_{t,k})^*)\end{aligned}$$

Comparing now the impact of a higher carbon price to the optimal, we can first clearly see that the damages from higher temperature will be lower under the higher carbon price than under the optimal one $d(T_t^o) < d(T_t^o)^*$, as temperature is lower since emissions are reduced at a higher rate. Similarly, abatement is higher under the higher carbon price. As such, we propose a sectoral-maroprudential policy, which will loosen the regulatory constraint on loans to the green sector. This policy will boost the relative share of the green sector in total output, which will partially offset the welfare loss, as the green sector is less carbon intensive[54].

Similarly, the sectoral-maroprudential policy will decrease the wedge on the labor component of welfare.

[52] Where we use policy functions approximated to the second order.

[53] First by using the fact that the utility function is strictly increasing. Then by using the economy budget constraint (and abstracting from adding–without a loss of generality–the investment adjustment costs as well as the price stickiness adjustment costs): $Y_t = C_t + I_t + G_t + Z_t$, and that $G_t = gY_t$, and $Z_t = f(.)Y_t$.

[54] Thus, abatement costs are less impacted by the rise in the carbon price in this sector.

C.6 Premium Distortion

Risk premia are defined as:

$$\begin{aligned} EP_{t,k} &= R_{t,k} - R_t \\ &= \frac{\alpha L_{t,k}^{1-\alpha}\epsilon_t^{t,k}\Psi_{t,k}d(T_t^o)K_t^{\alpha-1} - (Q_{t,k}-\delta)}{Q_{t-1,k}} - R_t \end{aligned}$$

At the steady state, as we chose $L_k = \bar{L}$ to march hours worked in the economy, the previous expression simplifies to:

$$\begin{aligned} EP_{t,k} &= \frac{\alpha \bar{L}^{1-\alpha}\epsilon_t^{t,k}\Psi_{t,k}d(T_t^o)K_t^{\alpha-1} - (Q_{t,k}-\delta)}{Q_{t-1,k}} - R_t \\ &= \frac{\alpha\Psi_{t,k}\frac{Y_{t,k}}{K_{t,k}} - (Q_{t,k}-\delta)}{Q_{t-1,k}} - R_t \end{aligned}$$

Thus, relying on a market-based instrument such as the ETS implies sudden changes and volatility in the carbon price. This uncertainty will generate fluctuations in the marginal cost components and in the price of capital, that will translate to volatility in risk premia. In the case of an increase in the carbon price:

- $MC_{t,k}$, which represents the maginal cost of firms would increase as a result of higher abatement costs ($MC_{t,k}$=$\Psi_{t,k}$+$\theta_{1,k}\mu_{t,k}^{\theta_{2,k}}$+$\tau_{t,k}(1-\mu_{t,k})\varphi_k$).
- Thus, firms' investment decreases, leading to a lower price of capital $Q_{t,k}$.

While a positive shock would trigger volatility in risk premia (as the price increase impacts all component in $R_{t,k}$), the direction of the change depends on the calibration. As such two cases arise:

1. $\alpha\Psi_{t,k}\frac{Y_{t,k}}{K_{t,k}} - (Q_{t,k}-\delta) > 0$.

In this case, risk premia would increase following a positive shock on the carbon price. Intuitively, the decrease in the price of capital is proportionally higher than the impact the shock would have on output, capital, and capital/labor input cost.

2. $\alpha\Psi_{t,k}\frac{Y_{t,k}}{K_{t,k}} - (Q_{t,k}-\delta) < 0$.

In this case, risk premia would decrease following a positive shock on the carbon price. Intuitively, the decrease in the price of capital cost is proportionally smaller than the impact the shock would have on output, capital, and capital/labor input cost.

In either case, it is possible to offset the level and volatility effect by acting on $Q_{t,k}$. From the macro-finance literature, we know that QE rules reacting to deviations in risk premia from their steady states are able to eliminate risk premia distortions. In our case, the distortion arises from a shock to the carbon price and not to the quality of capital.

C.7 Balanced Growth Path Equilibrium

C.7.1 The Firms

In order to perform our structural parameters estimation through the simulated method of moments, we first need to specify the de-trended economy over its balanced growth path.

The growth rate of Γ_t determines the growth rate of the economy along the balanced growth path.[55] This growth rate is denoted by γ^Y, where:

$$\Gamma_t = \gamma^Y \Gamma_{t-1} \tag{136}$$

Stationary variables are denoted by lower case letters, whereas variables that are growing are denoted by capital letters. For example, in the growing economy, output in each sector is denoted by $Y_{t,k}$. De-trended output is thus obtained by dividing output in the growing economy by the level of growth progress:

$$y_{t,k} = \frac{Y_{t,k}}{\Gamma_t} \tag{137}$$

Sectoral emissions, which we denote by $E_{t,k}$, in the growing economy are given as follows:

$$E_{t,k} = (1 - \mu_{t,k})\varphi_k Y_{t,k} Dpt, k \tag{138}$$

Thus, in the de-trended economy, per sector emissions law of motion reads as follows:

$$e_{t,k} = (1 - \mu_{t,k})\varphi_k y_{t,k} Dpt, k \tag{139}$$

where:

$$e_{t,k} = \frac{E_{t,k}}{\Gamma_t} \tag{140}$$

[55] In our setup both sectors grow at the same rate Γ_t.

and the price dispersion $D_{tp,k}$ is a stationary variable[56].

Therefore, the total flow of emissions reads as:

$$e_t = \frac{E_t}{\Gamma_t} \tag{141}$$

The abatement cost in the growing economy is:

$$Z_{t,k} = (1 - f(\mu_{t,k}))Y_{t,k}Dpt, k \tag{142}$$

Thus, in the de-trended economy, the abatement cost reads as follows:[57]

$$z_{t,k} = (1 - f(\mu_{t,k}))y_{t,k}Dpt, k \tag{143}$$

The stock of emissions in the atmosphere is denoted by X_t, while the temperature is called T_t^o in the growing economy:

$$X_t = (1 - \gamma_d)X_{t-1} + E_t + E_t^* \tag{144}$$

$$T_t^o = \upsilon_1^o(\upsilon_2^o X_{t-1} - T_{t-1}^o) + T_{t-1}^o, \tag{145}$$

The de-trended X_t and T_t^o read as follows:

$$x_t = \frac{(1 - \gamma_d)}{\gamma^Y} x_{t-1} + e_t + E^* \tag{146}$$

$$\gamma^Y t_t^o = \upsilon_1^o(\upsilon_2^o x_{t-1} - t_{t-1}^o) + t_{t-1}^o \tag{147}$$

where:

$$x_t = \frac{X_t}{\Gamma_t} \tag{148}$$

$$t_t^o = \frac{T_t^o}{\Gamma_t} \tag{149}$$

In the growing economy, with the above growth progress, the production function is as follows:

[56] In the baseline case (i.e. the Rotemberg case), the term $D_{tp,k}$ collapses (i.e. $D_{tp,k} = 1$). Only when relying on Calvo pricing that the dispersion appears.

[57] Please note that $\mu_{t,k}$ is stationary.

$$Y_{t,k} = \varepsilon_t^A d(T_t^o) K_{t,k}^{\alpha} (\Gamma_t L_{t,k})^{1-\alpha} Dpt, k \tag{150}$$

where per sector labor $L_{t,k}$ and the technology shock $\varepsilon_t^{A_k}$ are stationary variables. Furthermore, the climate damage function captures the growth rate Γ_t such that $d(T_t^o) = ae^{-\frac{b}{\Gamma_t^2} T_t^{o2}}$. Capturing the growth rate of the economy within the damage function allows us to simplify the de-trended form of the damage function without a loss of generality as over the studied period (a 10-15 year horizon) $d(T_t^o) = ae^{-\frac{b}{\Gamma_t^2} T_t^{o2}} \approx ae^{-bT_t^{o2}}$.

De-trending the production function gives the following:

$$y_{t,k} = \varepsilon_t^A d(t_t^o) k_{t,k}^{\alpha} L_{t,k}^{1-\alpha} Dpt, k^{-1} \tag{151}$$

As for aggregate emissions, the de-trended aggregate output reads as:

$$y_t = \frac{Y_t}{\Gamma_t} \tag{152}$$

The capital-accumulation equation for both the green and brown sectors in the growing economy read as:

$$K_{t,k} = (1-\delta) K_{t-1,k} + I_{t-1,k} \tag{153}$$

In the de-trended economy, we thus have:

$$k_{t,k} = \gamma^{Y^{-1}} [(1-\delta) k_{t-1,k} + i_{t-1,k}] \tag{154}$$

with both capital and investment de-trended variables reading as: $k_{t,k} = \frac{K_{t,k}}{\Gamma_t}$ and$i_{t,k} = \frac{I_{t,k}}{\Gamma_t}$, respectively.[58]

C.7.2 The Economy Constraint (Rotemberg case)

The economy budget constraint reads as:

$$Y_t = C_t + I_t + G_t + Z_t + \sum_k g(\varkappa)[f_k(.) I_{t,k}] + \sum_k g(\varkappa)[\Delta_{t,k}^P] Y_t \tag{155}$$

Thus,

$$y_t = c_t + i_t + g_t + z_t + \sum_k g(\varkappa)[f_k(.) i_{t,k}] + \sum_k g(\varkappa)[\Delta_{t,k}^P] y_t \tag{156}$$

[58]We note that both the return on capital $R_{t,k}^k$ and wage $W_{t,k}$ are stationary. This can be easily seen by looking at the intermediate firms FOC.

where: $c_t = \frac{C_t}{\Gamma_t}$.

The calvo case reads as:

$$y_t = c_t + i_t + g_t + z_t + \sum_k g(\varkappa)[f_k(.)i_{t,k}] \tag{157}$$

C.7.3 Households

Under the presence of a labor-augmenting technology Γ_t, the utility function reads as: $U(C_t) = \frac{(C_t - hC_{t-1})^{1-\sigma}}{1-\sigma}$.

Thus, the de-trended utility reads as:

$$\sum_{t=0}^{\infty} \beta^t U(c_t) = \sum_{t=0}^{\infty} \tilde{\beta}^t \left(\frac{(c_t - (\gamma^Y)^{-1} h c_{t-1})^{1-\sigma}}{1-\sigma} \right) \tag{158}$$

where $\tilde{\beta} = \beta\gamma^{1-\sigma}$.

Turning to households, the equilibrium de-trended conditions read as:

$$\varrho_t = (c_t - h(\gamma^Y)^{-1} c_{t-1})^{-\sigma} - \tilde{\beta}(\gamma^Y)^{-1} h E_t \left\{ (c_{t+1} - h(\gamma^Y)^{-1} c_t)^{-\sigma} \right\} \tag{159}$$

$$1 = \tilde{\beta} E_t \Lambda_{t,t+1} R_{t+1} \tag{160}$$

with $\Lambda_{t-1,t} = \frac{\varrho_t}{\varrho_{t-1}}$ the expected variation in the marginal utility of consumption.

C.7.4 The Firms Monetary Aggregates (NK related variables)

The presence of trend growth in output will impact the NK variables. Hence, the stationarized New Phillips Curve reads as:

$$\theta^P \pi_{t,k}(\pi_{t,k} - 1) = \left(\frac{P_{t,k}}{P_t} \right)^{-\theta} \left(\frac{P_{t,k}}{P_t}(1-\theta_k) + \theta_k MC_{t,k} \right) + E_t \left\{ \gamma^Y \tilde{\beta} \Lambda_{t,t+1} \frac{Y_{t+1}}{Y_t} \theta^P \pi_{t+1,k}(\pi_{t+1,k} - 1) \right\} \tag{161}$$

Turning now to the Calvo case, we stationarize $S_{t,k}$, $\Upsilon_{t,k}$, and $\Theta_{t,k}$, dividing these variables by the trend Γ_t. The NK Philips Curve stationary equations are as follows:

$$s_{t,k} = P_{t,k}^{\theta_k - \theta} \Psi_{t,k} y_t + \gamma^Y \frac{\varrho_{t+1}}{\varrho_t} \xi \tilde{\beta} \mathbb{E}_t \pi_{t+1}^{\theta} s_{t+1,k}, \tag{162}$$

$$\theta_{t,k} = P_{t,k}^{\theta_k - \theta} y_t + \gamma^Y \frac{\varrho_{t+1}}{\varrho_t} \xi \tilde{\beta} \mathbb{E}_t \pi_{t+1}^{\theta - 1} \theta_{t+1,k}, \tag{163}$$

$$\upsilon_{t,k} = P_{t,k}^{\theta_k - \theta} \left[\theta_{1,k} \mu_{t,k}^{\theta_{2,k}} + \tau_{et,k}(1 - \mu_{t,k}) \varphi_k \right] y_t + \gamma^Y \frac{\varrho_{t+1}}{\varrho_t} \xi \tilde{\beta} \mathbb{E}_t \pi_{t+1}^{\theta} \upsilon_{t+1,k}. \tag{164}$$

C.7.5 Government

The lump sum taxes T_t and government spending G_t grow at the growth rate of the economy Γ_t:

$$g_t = t_t + \tau_t e_t, \tag{165}$$

with $T_t = t_t \Gamma_t$.

C.7.6 Capital Producing Firms

The de-trended tobin Q reads as:

$$Q_{t,k} = 1 + f_k(.) + f_k'(.) \left(\gamma^Y \frac{i_{t,k}}{i_{t-1,k}} \right) - \tilde{\beta} E_t \left\{ \Lambda_{t,t+1} f_k'(.) \left(\gamma^Y \frac{i_{t+1,k}}{i_{t,k}} \right)^2 \right\}. \tag{166}$$

C.7.7 Financial Intermediaries

All financial intermediary variables are made stationary by dividing aggregate variables by the trend Γ_t. The only equation that needs to be adjusted is the net worth of bankers. Therefore, the stationary net worth of bankers reads as:

$$N_t = {\gamma^Y}^{-1} \left(\theta_B [(R_{t,g} - R_t) Q_{t-1,g} S_{t-1,g} + (R_{t,d} - R_t) Q_{t-1,d} S_{t-1,d}] + (\theta_B R_t + \omega) N_{t-1} \right). \tag{167}$$

D Appendix: Additional Figures

FIGURE 17. Implications of transition pathways (Net-Zero) Without and With Macroprudential Policy

Notes: As a robustness exercise, we compare a pathway consistent with the net-zero objective where a macroprudential policy takes into account climate risk and where it does not. The blue line corresponds to the case where no climate risk is considered ($\lambda_g = 1$ and $\lambda_b = 1$) and the green line corresponds to the case where the macroprudential authority considers climate risk with a progressive change in sectoral risk-weights ($\lambda_g \rightarrow 0.75$ and $\lambda_b = 1$) .

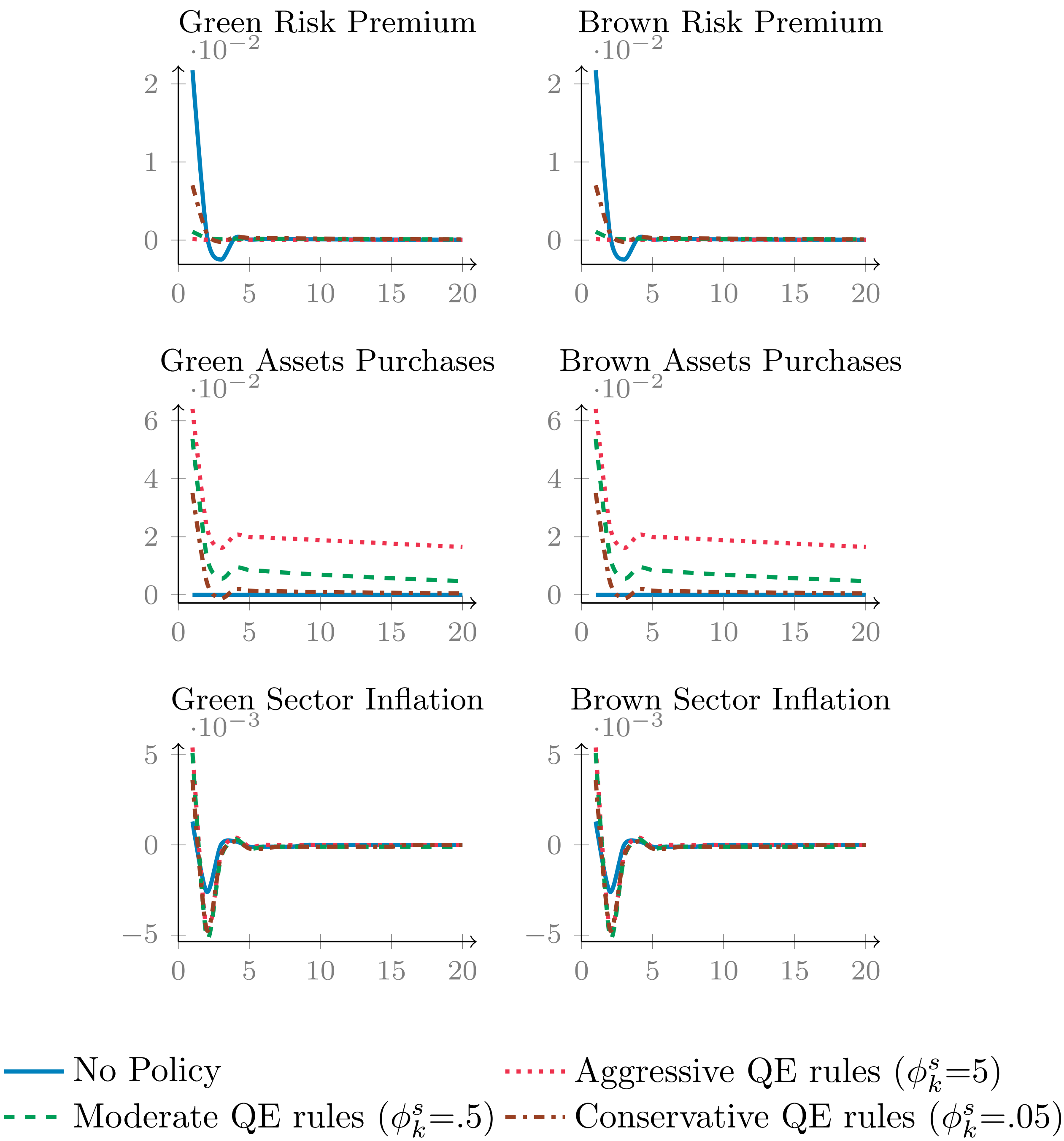
FIGURE 18. Implications of transition pathways (Net-Zero) Without and With Macroprudential Policy

Notes: As a robustness exercise, we compare a pathway consistent with the net-zero objective where a macroprudential policy takes into account climate risk and where it does not. The blue line corresponds to the case where no climate risk is considered ($\lambda_g = 1$ and $\lambda_b = 1$) and the green line corresponds to the case where the macroprudential authority considers climate risk with a progressive change in sectoral risk-weights ($\lambda_g \to 0.65$ and $\lambda_b = 1$) .

FIGURE 19. Implications of transition pathways (Net-Zero) Without and With Macroprudential Policy

Notes: As a robustness exercise, we compare a pathway consistent with the net-zero objective where a macroprudential policy takes into account climate risk and where it does not. The blue line corresponds to the case where no climate risk is considered ($\lambda_g = 1$ and $\lambda_b = 1$) and the green line corresponds to the case where the macroprudential authority considers climate risk with a progressive change in sectoral risk-weights ($\lambda_g \to 0.45$ and $\lambda_b = 1$) .

FIGURE 20. Responses to a positive carbon price shock (ε_t^τ). (The Calvo Case)



Notes: The figure shows the effect of a positive carbon price shock (ε_t^τ) calibrated on the ETS data on selected variables, with and without QE policy rules. The results are presented as percentage deviations from the steady state over quarterly periods.