Online Appendix

The Unequal Economic Consequences of Carbon Pricing

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Contents

A. Data **3**
A.1. Details on regulatory events . . . 3
A.2. Macro data . . . 5
A.3. Micro data . . . 6
A.3.1. LCFS . . . 6
A.3.2. LFS . . . 9
A.3.3. BSA . . . 9

B. Additional Charts and Tables **10**
B.1. Diagnostics of the surprise series . . . 10
B.2. More on aggregate effects . . . 12
B.2.1. Internal instrument approach . . . 12
B.2.2. Local projection-instrumental variable approach . . . 12
B.2.3. Core versus headline HICP . . . 15
B.2.4. Variance Decomposition . . . 16
B.2.5. Financial conditions and uncertainty . . . 17
B.2.6. Aggregate effects for the UK . . . 18
B.3. More on heterogeneous effects . . . 19
B.3.1. Further descriptive statistics . . . 19
B.3.2. Aggregate expenditure responses . . . 20
B.3.3. Smoothing impulse responses . . . 21
B.3.4. Group differences . . . 22
B.3.5. Robustness concerning grouping . . . 23
B.3.6. Selection . . . 24
B.3.7. What drives the income response? . . . 27
B.3.8. External validity . . . 30
B.3.9. Attitudes towards climate policy . . . 31
B.4. Additional results from heterogeneous-agent climate-economy model 32

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C. Sensitivity Analysis **36**
C.1. Instrument construction 36
C.2. Confounding news 44
C.3. Sample and specification choices 49

D. A heterogeneous-agent climate-economy model: Derivations **55**
D.1. Households 55
D.2. Firms 62
D.3. Climate block 68
D.4. Fiscal and monetary policy 69
D.5. Aggregation and market clearing 69
D.6. Equilibrium 70
D.7. Calibration 72
D.8. Steady state and model solution 74

References Appendix **76**

A. Data

A.1. Details on regulatory events

In this Appendix, I provide a detailed list of all the regulatory events used in the paper. To collect the events, I relied on a number of different sources. After 2010, most of the relevant news can be found on the European Commission Climate Action news archive: https://ec.europa.eu/clima/news/news_archives_en. Before that, I used information from the official journal of the European Union: https://eur-lex.europa.eu/homepage.html. Finally, the decisions on the NAPs in the first two phases are taken from Mansanet-Bataller and Pardo (2009). Table A.1 lists all the events.

Table A.1: Regulatory Update Events

	Date	Event description	Type
1	25/05/2005	Italian phase I NAP approved	Free alloc.
2	20/06/2005	Greek phase I NAP approved	Free alloc.
3	23/11/2005	Court judgement on proposed amendment to NAP, UK vs Commission	Free alloc.
4	22/12/2005	Further guidance on allocation plans for the 2008–2012 trading period	Cap
5	22/02/2006	Final UK Phase I NAP approved	Free alloc.
6	23/10/2006	Stavros Dimas delivered the signal to tighten the cap of phase II	Cap
7	13/11/2006	Decision avoiding double counting of emission reductions for projects under the Kyoto Protocol	Intl. credits
8	29/11/2006	Commission decision on the NAP of several member states	Free alloc.
9	14/12/2006	Decision determining the respective emission levels of the community and each member state	Cap
10	16/01/2007	Phase II NAPs of Belgium and the Netherlands approved	Free alloc.
11	05/02/2007	Slovenia phase II NAP approved	Free alloc.
12	26/02/2007	Spain phase II NAP approved	Free alloc.
13	26/03/2007	Phase II NAPs of Poland, France and Czech Republic approved	Free alloc.
14	02/04/2007	Austrian phase II NAP approved	Free alloc.
15	16/04/2007	Hungarian phase II NAP approved	Free alloc.
16	30/04/2007	Court order on German NAP, EnBW AG vs Commission	Free alloc.
17	04/05/2007	Estonian phase II NAP approved	Free alloc.
18	15/05/2007	Italian phase II NAP approved	Free alloc.
19	07/11/2007	Court judgement on German NAP, Germany vs Commission	Free alloc.
20	08/04/2008	Court order on German NAP, Saint-Gobain Glass GmbH vs Commission	Free alloc.
21	23/04/2009	Directive 2009/29/EC amending Directive 2003/87/EC to improve and extend the EU ETS	Cap
22	23/09/2009	Court judgement on NAP, Poland vs Commission	Free alloc.
23	24/12/2009	Decision determining sectors and subsectors which have a significant risk of carbon leakage	Free alloc.
24	19/04/2010	Commission accepts Polish NAP for 2008-2012	Free alloc.
25	09/07/2010	Commission takes first step toward determining cap on emission allowances for 2013	Cap
26	14/07/2010	Member states back Commission proposed rules for auctioning of allowances	Auction
27	22/10/2010	Cap on emission allowances for 2013 adopted	Cap
28	12/11/2010	Commission formally adopted the regulation on auctioning	Auction
29	25/11/2010	Commission presents a proposal to restrict the use of credits from industrial gas projects	Intl. credits
30	15/12/2010	Climate Change Committee supported the proposal on how to allocate emissions rights	Free alloc.
31	21/01/2011	Member states voted to support the ban on the use of certain industrial gas credits	Intl. credits
32	15/03/2011	Commission proposed that 120 million allowances to be auctioned in 2012	Auction
33	22/03/2011	Court judgement on NAP, Latvia vs Commission	Free alloc.
34	29/03/2011	Decision on transitional free allocation of allowances to the power sector	Free alloc.
35	27/04/2011	Decision 2011/278/EU on transitional Union-wide rules for harmonized free allocation of allowances	Free alloc.
36	29/04/2011	Commission rejects Estonia's revised NAP for 2008-2012	Free alloc.
37	07/06/2011	Commission adopts ban on the use of industrial gas credits	Intl. credits
38	13/07/2011	Member states agree to auction 120 million phase III allowances in 2012	Auction
39	26/09/2011	Commission sets the rules for allocation of free emissions allowances to airlines	Free alloc.
40	14/11/2011	Clarification on the use of international credits in the third trading phase	Intl. credits
41	23/11/2011	Regulation 1210/2011 determining the volume of allowances to be auctioned prior to 2013	Auction
42	25/11/2011	Update on preparatory steps for auctioning of phase 3 allowances	Auction
43	05/12/2011	Commission decision on revised Estonian NAP for 2008-2012	Free alloc.
44	29/03/2012	Court judgments on NAPs for Estonia and Poland	Free alloc.
45	02/05/2012	Commission publishes guidelines for review of GHG inventories in view of setting national limits for 2013-20	Cap
46	23/05/2012	Commission clears temporary free allowances for power plants in Cyprus, Estonia and Lithuania	Free alloc.
47	05/06/2012	Commission publishes guidelines on State aid measures in the context of the post-2012 trading scheme	Free alloc.

	Date	Event description	Type
48	06/07/2012	Commission clears temporary free allowances for power plants in Bulgaria, Czech Republic and Romania	Free alloc.
49	13/07/2012	Commission rules on temporary free allowances for power plants in Poland	Free alloc.
50	25/07/2012	Commission proposed to backload certain allowances from 2013-2015 to the end of phase III	Auction
51	12/11/2012	Commission submits amendment to back-load 900 million allowances to the years 2019-2020	Auction
52	14/11/2012	Commission presents options to reform the ETS to address growing supply-demand imbalance	Cap
53	16/11/2012	Auctions for 2012 aviation allowances put on hold	Auction
54	30/11/2012	Commission rules on temporary free allowances for power plants in Hungary	Free alloc.
55	25/01/2013	Update on free allocation of allowances in 2013	Free alloc.
56	28/02/2013	Free allocation of 2013 aviation allowances postponed	Free alloc.
57	25/03/2013	Auctions of aviation allowances not to resume before June	Auction
58	16/04/2013	The European Parliament voted against the Commission's back-loading proposal	Auction
59	05/06/2013	Commission submits proposal for international credit entitlements for 2013 to 2020	Intl. credits
60	03/07/2013	The European Parliament voted for the carbon market back-loading proposal	Auction
61	10/07/2013	Member states approve addition of sectors to the carbon leakage list for 2014	Free alloc.
62	30/07/2013	Update on industrial free allocation for phase III	Free alloc.
63	05/09/2013	Commission finalized decision on industrial free allocation for phase three	Free alloc.
64	26/09/2013	Update on number of aviation allowances to be auctioned in 2012	Auction
65	08/11/2013	Member states endorsed negotiations on the back-loading proposal	Auction
66	21/11/2013	Commission submitted non-paper on back-loading to the EU Climate Change Committee	Auction
67	10/12/2013	European Parliament voted for the back-loading proposal	Auction
68	11/12/2013	Climate Change Committee makes progress on implementation of the back-loading propsal	Auction
69	18/12/2013	Commission gives green light for a first set of member states to allocate allowances for calendar year 2013	Free alloc.
70	08/01/2014	Climate Change Committee agrees back-loading	Auction
71	22/01/2014	Commission proposed to establish a market stability reserve for phase V	Cap
72	26/02/2014	Commission gives green light for free allocation by all member states	Free alloc.
73	27/02/2014	Back-loading: 2014 auction volume reduced by 400 million allowances	Auction
74	13/03/2014	Commission approves first batch of international credit entitlement tables	Intl. credits
75	28/03/2014	Commission approves second batch of international credit entitlement tables	Intl. credits
76	04/04/2014	Update on approval of international credit entitlement tables	Intl. credits
77	11/04/2014	Commission approves four more international credit entitlement tables	Intl. credits
78	23/04/2014	Commission approves final international credit entitlement tables	Intl. credits
79	02/05/2014	Commission published the number of international credits exchanged	Intl. credits
80	05/05/2014	Commission submits proposed carbon leakage list for 2015-2019	Free alloc.
81	04/06/2014	Auctioning of aviation allowances to restart in September	Auction
82	04/07/2014	Commission published the first update on the allocation of allowances from the New Entrants' Reserve	Free alloc.
83	09/07/2014	Climate Change Committee agrees proposed carbon leakage list for the period 2015-2019	Free alloc.
84	27/10/2014	Commission adopts the carbon leakage list for the period 2015-2019	Free alloc.
85	04/11/2014	Updated information on exchange and international credit use	Intl. credits
86	04/05/2015	Updated information on exchange and international credit use	Intl. credits
87	15/07/2015	Proposal to revise the EU emissions trading system for the period after 2020	Cap
88	23/07/2015	Commission publishes status update for New Entrants' Reserve and allocation reductions	Free alloc.
89	04/11/2015	Updated information on exchange and international credit use	Intl. credits
90	15/01/2016	Commission publishes status update for New Entrants' Reserve	Free alloc.
91	28/04/2016	Court judgment on free allocation in the EU ETS for the period 2013-2020	Free alloc.
92	02/05/2016	Updated information on exchange and international credit use	Intl. credits
93	23/06/2016	Following court judgement, commission to modify cross-sectoral correction factor for 2018-2020	Free alloc.
94	15/07/2016	Commission published a status update on the allocation of allowances from the New Entrants' Reserve 2013-2020	Free alloc.
95	08/09/2016	Court judgment on free allocation in the EU ETS for the period 2013-2020	Free alloc.
96	04/11/2016	Updated information on exchange and international credit use	Intl. credits
97	16/01/2017	Commission publishes status update for New Entrants' Reserve	Free alloc.
98	24/01/2017	Commission adopts Decision to implement Court ruling on the cross-sectoral correction factor	Free alloc.
99	15/02/2017	European Parliament voted in support of the revision of the ETS Directive for the period after 2021	Cap
100	27/04/2017	Climate Change Committee approves technical changes to auction rules	Auction
101	02/05/2017	Updated information on exchange and international credit use	Intl. credits
102	12/05/2017	Commission publishes first surplus indicator for ETS Market Stability Reserve	Auction
103	17/07/2017	Commission publishes status update for New Entrants' Reserve	Free alloc.
104	26/07/2017	Court judgment again confirms benchmarks for free allocation of ETS allowances for 2013-2020	Free alloc.
105	06/11/2017	Updated information on exchange and international credit use	Intl. credits
106	15/01/2018	Commission publishes status update for New Entrants' Reserve	Free alloc.
107	04/05/2018	Updated information on exchange and international credit use	Intl. credits
108	08/05/2018	Commission Notice on the preliminary carbon leakage list for phase IV (2021-2030)	Free alloc.
109	15/05/2018	ETS Market Stability Reserve will start by reducing auction volume by almost 265 million allowances	Auction
110	16/07/2018	Commission publishes status update for New Entrants' Reserve	Free alloc.
111	30/10/2018	Commission adopts amendment to ETS auctioning regulation	Auction
112	06/11/2018	Updated information on exchange and international credit use	Intl. credits
113	05/12/2018	Poland's 2019 auctions to include some allowances not used for power sector modernization	Auction
114	04/01/2019	Amendment to the ETS auctioning regulation	Auction
115	15/01/2019	Commission publishes status update for New Entrants' Reserve	Free alloc.
116	15/02/2019	Adoption of the Delegated Decision on the carbon leakage list for 2021-2030	Free alloc.
117	23/04/2019	Iceland, Liechtenstein and Norway to start auctions on the common auction platform soon	Auction
118	15/05/2019	ETS Market Stability Reserve to reduce auction volume by almost 400 million allowances	Auction
119	16/05/2019	Revised 2019 auction calendars including EEA EFTA volumes published	Auction
120	12/06/2019	Poland's 2020 auction volume to include allowances not used for power sector modernisation	Auction
121	19/06/2019	Updated information on exchange and international credit use	Intl. credits
122	11/07/2019	2020 and revised 2019 auction calendars of the common auction platform published	Auction
123	15/07/2019	Commission publishes status update for New Entrants' Reserve	Free alloc.

	Date	Event description	Type
124	28/08/2019	Commission amends ETS auctioning regulation for phase 4	Auction
125	31/10/2019	Commission adopts the Regulation on adjustments to free allocation due to activity level changes	Free alloc.
126	08/11/2019	Auctioning regulation amendment for phase 4 of the EU ETS published and to enter into force	Auction

A.2. Macro data

In this Appendix, I provide details on the macroeconomic data used in the paper, including information on the data source and coverage.

Table A.2: Data Description, Sources, and Coverage

Variable	Description	Source	Sample
Instrument			
LEXC.01 (PS)	EUA futures front contract (settlement price)	Datastream	22/04/2005-31/12/2019
ELECWAVG	Wholesale electricity price, constructed as weighted average of EEX, APX, Nordpool, Powernext, OMEL, GME, and the EPX spot price, converted to EUR/tCO2 using GHG emissions intensity of electricity generation	Datastream/European Environment Agency/own calculations	22/04/2005-31/12/2019
Baseline variables			
EKESCPENF	HICP energy (EA-19)	Datastream	1999M1-2019M12
GHGTOTAL	Total GHG emissions excluding LULUCF and including international aviation (EU)	Eurostat/own calculations	1999M1-2019M12
EKCPHARMF	HICP all items (EA-19)	Datastream	1999M1-2019M12
EKIPTOT.G	Industrial production excl. construction (EA-19)	Datastream	1999M1-2019M12
EMECB2Y.	Two-year government bond yield	Datastream	1999M1-2019M12
EKESUNEMO	Unemployment rate (EA-19)	Datastream	1999M1-2019M12
DJSTOXX	Euro STOXX	Datastream	1999M1-2019M12
DCOILBRENTEU	Brent Crude price	FRED	1999M1-2019M12
Additional variables			
Other carbon futures	LEXC.0h (PS), for h in $(2, 3, 4, 5)$	Datastream	22/04/2005-31/12/2019
BAMLHE00EHYIOAS	ICE BofA euro high yield index option-adj. spread	FRED	1999M1-2019M12
VSTOXX	Euro STOXX 50 volatility	stoxx.com	1999M1-2019M12
EKGDP...D	Real GDP (EA-19)	Datastream	1999Q1-2019Q4
EKESENMZD	Final consumption expenditure (EA-19)	Datastream	1999Q1-2019Q4
EKGFCF..D	Gross fixed capital formation (EA-19)	Datastream	1999Q1-2019Q4
EMESJSABB	Wages and salaries: all activities	Datastream	1999Q1-2019Q4
CCPATENTS	Share of climate change mitigation technologies (CCMT) patents filed at EPO	Google Patents Public Data/own calculations	2005Q1-2019Q4

The transformed series used in the baseline VAR are depicted in Figure A.1.

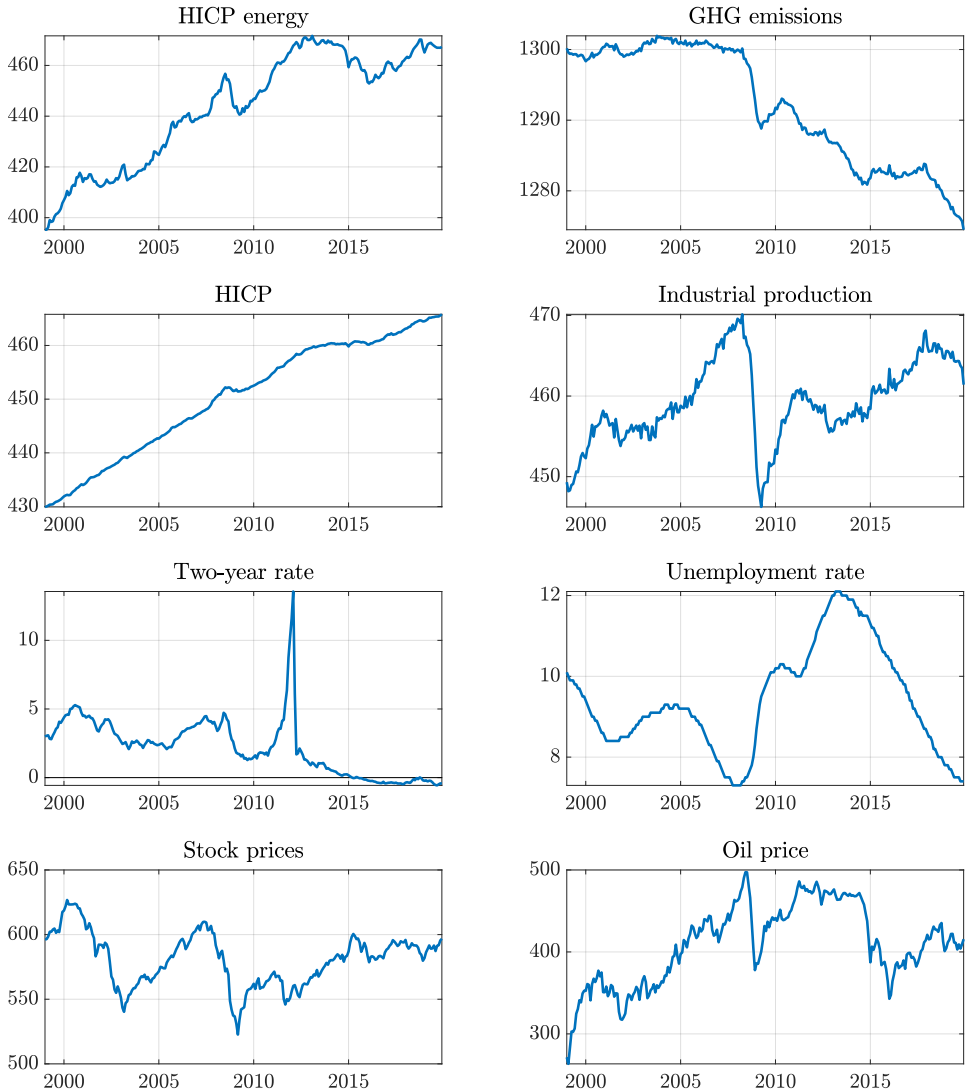


Figure A.1: Transformed Data Series

A.3. Micro data

In this Appendix, I provide detailed information on the micro data used in Sections 5 and 6 of the paper. I use data from a selection of different surveys, which are discussed in detail below.

A.3.1. LCFS

The living costs and food survey (LCFS) data can be obtained from the UK Data Service. I use the waves from 1999-2001 of the Family Expenditure Survey, the 2001-2007 waves from the Expenditure and Food Survey and the 2008-2019 waves from the LCFS, which superseded the previous two surveys. Note that within this sample, the reporting frequency changed two times first from financial year to calendar year and then back again to the financial year format. The waves

are adjusted to consistently reflect the calendar year prior to creating the pooled cross-section. Most variables of interest are available in the derived household datasets. The age at which full-time education was completed, as well as current wages, is aggregated from the personal derived datasets.

As the main measure of expenditure, I use total expenditure excluding housing (p550tp-p536tp). For current income, I use current total disposable income, calculated by subtracting income taxes and NI contributions from the gross income (p352p-p392p-p388p-p029hp). I group the households by their normal disposable income (p389p). For earnings, I use wages net of taxes (aggregate p004p to the household level, subtract current taxes and add back taxes on financial income p068h). For financial income, I use p324p, which includes interest income, dividends and rents. For age, I use the age of the household reference person, p396p. Education is proxied by the highest age a person in the household has completed a full-time education (a010 aggregated to the household level). The housing tenure status is recorded in variable a121.

For energy expenditure, I use expenditure on fuel, light and power (p537t). Constructing measures of non-durable, services and durable expenditure is not trivial in the LCFS data, as the broader available expenditure categories do not allow a clean split, e.g. personal goods and services (p544t) is a mix of non-durable goods and services while household goods (p542t) includes both non-durable and durable goods. To construct clean measures of non-durables, services and durables expenditure, I split these broader subcategories into non-durable, services and durable parts by grouping the items in a particular subcategory accordingly, following closely the COICOP guidelines. A further challenge in doing so is that the code names for disaggregated expenditure items changed when the FES became the EFS in 2001. In Table A.3, I detail how the non-durable, services and durable expenditure measures are constructed. At the item level, I provide both, the relevant codes in the FES and the EFS/LCFS. Note that semi-durables are subsumed under non-durables, and services do not include housing.

Table A.3: Expenditure Classification in LCFS

Category	Subcategories	Items
Non-durables	Fuel, light power (p537t)	
	Food, alcoholic drinks, tobacco (p538t, p539t, p540t)	
	Clothing and footwear (p541t)	
	Non-durable household goods (subset of p542t)	*LCFS codes:* c52111t, c52112t, c53311t, c55214t, c56111t, c56112t, c56121t, c56123t, c93114t, c93313t, c93411t, c95311t, c95411t, cc1311t *FES codes:* d070104t, d070105t, d070211t, d070209t, d070401t, d070402t, d070302t, d070601t, d120304t, d070501t

Category	Subcategories	Items
	Non-durable personal goods (subset of p544t)	*LCFS codes:* c61112t, c61211t, c61311t, c61313t, cc1312t, cc1313t, cc1314t, cc1315t, cc1316t, cc1317t, cc3211t, cc3222t, cc3223t, cc3224t *FES codes:* d090402t, d090102t, d090501t, d090101t, d090103t, d090104t, d090105t, d090301t, d090202t, d090302t, d090303t
	Non-durable motoring expenditure (subset of p545t)	*LCFS codes:* c72114t, c72211t, c72212t, c72213t *FES codes:* d100405t, d100301t, d100302t, d100303t
	Non-durable leisure goods (subset of p547t)	*LCFS codes:* c91126t, c91411t, c91412t, c91413t, c91414t, c93111t, c93113t, c93311t, c95111t, c95211t, c95212t *FES codes:* d120114t, d120108t, d120110t, d120109t, d120401t, d120113t, d070703t, d120303t, d120301t, d120302t
	Miscellaneous non-durable goods (subset of p549t)	*LCFS codes:* ck5511c, cc3221t *FES codes:* d070801t, d140601c, d090701t
Services	Household services (p543t)	
	Fares and other travel costs (p546t)	
	Leisure services (p548t)	
	Service part of household goods (subset of p542t)	*LCFS codes:* c53312t, c53313t, c53314t, c93511t, cc5213t *FES codes:* d070212t, d070213t
	Personal services (subset of p544t)	*LCFS codes:* c61111t, c61312t, c62111t, c62112t, c62113t, c62114t, c62211t, c62212t, c62311t, c62321t, c62322t, c62331t, c63111t, cc1111t *FES codes:* d090401t, d090502t, d090403t, d090404t, d090601t
	Service part of motoring expenditure (subset of p545t)	*LCFS codes:* b187-b179, b188, b249, b250, b252, c72313t, c72314t, c72411t, c72412t, c72413t, ck3112t, c72311c, c72312c, cc5411c *FES codes:* b187-b179, b188, b249, b250, b252, d100403t, d100406t, d100407t, d100404t, d100408t, d100201c, d100204c, d100401c
	Leisure services (subset of p547t)	*LCFS codes:* c91511t, c93112t, c94238t, c94239t, c94246t *FES codes:* d120111t, d120112t
	Miscellaneous services (subset of p549t)	*LCFS codes:* b237, b238, ck5315c, ck5213t, ck5214t *FES codes:* b237, b238, d140402, d140406c
Durables	Durable household goods (subset of p542t)	*LCFS codes:* b270, b271, c51111c, c51211c, c51212t, c51113t, c51114t, c53111t, c53121t, c53122t, c53131t, c53132t, c53133t, c53141t, c53151t, c53161t, c53171t, c53211t, c54111t, c54121t, c54131t, c54132t, c55111t, c55112t, c55213t, c56122t, c93212t, c93312t, c93412t, cc1211t *FES codes:* b270, b271, d070101c, d070102c, d070103t, d070304t, d070704t, d070203t, d070202t, d070204t, d070207t, d070208t, d070201t, d070206t, d070303t, d070301t, d070205t, d070701t, d070305t, d070306t, d070702t, d070602t
	Durable personal goods (subset of p544t)	*LCFS codes:* cc3111t *FES codes:* d090201t
	Durable motoring expenditure (subset of p544t)	*LCFS codes:* b244, b2441, b245, b2451, b247, c31315t, c71112t, c71122t, c71212t, c92114t, c92116t, c71111c, c71121c, c71211c, c92113c, c92115c, c72111t, c72112t, c72113t, c91112t *FES codes:* b244, b245, b247, d100105t, d100106t, d100107t, d100101c, d100102c, d100104c, d100203t, d100202t, d100205t

Category	Subcategories	Items
	Durable leisure goods (subset of p547t)	*LCFS codes:* c91124t, c82111t, c82112t, c82113t, c91111t, c91113t, c91121t, c91122t, c91123t, c91125t, c91211t, c91311t, c92211t, c92221t, c93211t *FES codes:* d120104t, d080202t, d080205t, d080207t, d120105t, d120101t, d120102t, d120103t, d120115t, d120402t, d120106t, d120107t, d120201t

Regarding the sample, I apply the following restrictions. I drop households that have a household reference person younger than 18 or older than 90 years. Furthermore, I drop households with a negative normal disposable income. To account for some (unrealistically) high or low values of consumption, for each quarter and income group, I drop the top and bottom 1% of observations for total expenditure.

A.3.2. LFS

To get information on the sector of employment, I use data from the UK Labour Force Survey (LFS). The LFS studies the employment circumstances of the UK population. It is the largest household study in the UK and provides the official measures of employment and unemployment. Apart from detailed information on employment, it also contains a wide range of related topics such as occupation, training, hours of work and personal characteristics of household members aged 16 years and over. The data can be obtained from the UK Data Service. I use the quarterly waves from 1999-2019 to construct a pooled cross-section. For the employment sector, I use the variable indsect, which describes the industry sector in the main job based on the SIC 2003 classification. To proxy income, I use the net pay from the main and second job (netwk and netwk2).

A.3.3. BSA

To proxy public attitudes towards climate policy, I use data from the British social attitudes (BSA) survey. The data can also be obtained from the UK Data Service. I use the waves from 1999-2019 to construct a pooled cross-section. To construct the income groups, I use the income quartiles that are provided from 2010 onwards (hhincq). For the years before, I use the household income variable (hhincome) to construct the quartiles. The survey contains many questions on the attitudes towards climate change, the environment and climate/environmental policy, but unfortunately most variables are not part of the main set of questions that are asked in every year. One exception concerns a question about taxes for car owners (cartaxhi), in particular it asks whether you agree with the following statement:

"For the sake of the environment, car users should pay higher taxes", which was fielded for all years up to 2017. Thus, I use the proportion of households agreeing with this statement as a proxy for the public attitude towards climate policy.

B. Additional Charts and Tables

In this Appendix, I present additional tables and figures that complement the analysis in the main body of the paper.

B.1. Diagnostics of the surprise series

As discussed in the paper, I perform a number of additional validity checks on the surprise series. In particular, I investigate the autocorrelation and forecastability of the surprise series as well as the relation to other shocks from the literature.

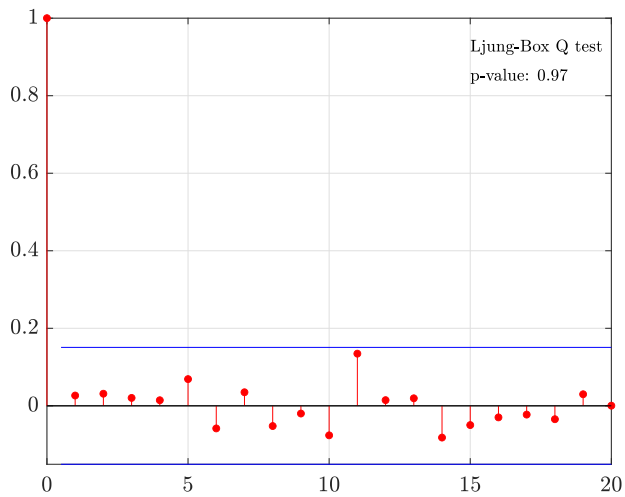


Figure B.1: The Autocorrelation Function of the Carbon Policy Surprise Series

Figure B.1 depicts the autocorrelation function. We can see that there is little evidence that the series is serially correlated. I also perform a series of Granger causality tests. Table B.1 shows that the series is not forecastable by past macroeconomic or financial variables. Finally, I look how the series correlates with other shock series from the literature and find that it is not correlated with other structural shock measures, including oil demand, uncertainty, financial, fiscal and monetary policy shocks, see Table B.2.[2] There is some weak correlation with oil supply shocks, which makes sense against the backdrop that the EU ETS also covers European oil producers in the North Sea.

[2] I thank Mario Alloza for kindly sharing their fiscal policy shock series.

Table B.1: Granger Causality Tests

Variable	p-value
Instrument	0.3279
EUA price	0.7060
HICP energy	0.7961
GHG emissions	0.6615
HICP	0.9949
Industrial production	0.7633
Two-year rate	0.5066
Unemployment rate	0.2473
Stock prices	0.7887
REER	0.1595
Oil price	0.3280
Joint	0.9339

Notes: The table shows the p-values of a series of Granger causality tests of the carbon policy surprise series using a selection of macroeconomic and financial variables.

Table B.2: Correlation with Other Shock Measures

Shock	Source	ρ	p-value	n	Sample
Monthly measures					
Global oil market					
Oil supply	Kilian (2008) (extended)	-0.16	0.10	104	2005M05-2013M12
	Kilian (2009) (updated)	-0.00	0.97	164	2005M05-2018M12
	Caldara, Cavallo, and Iacoviello (2019)	-0.11	0.24	128	2005M05-2015M12
	Baumeister and Hamilton (2019)	-0.15	0.04	176	2005M05-2019M12
	Känzig (2021) (updated)	0.12	0.11	176	2005M05-2019M12
Global demand	Kilian (2009) (updated)	-0.09	0.27	164	2005M05-2018M12
	Baumeister and Hamilton (2019)	-0.07	0.35	176	2005M05-2019M12
Oil-specific demand	Kilian (2009) (updated)	0.10	0.21	164	2005M05-2018M12
Consumption demand	Baumeister and Hamilton (2019)	0.13	0.10	176	2005M05-2019M12
Inventory demand	Baumeister and Hamilton (2019)	0.02	0.78	176	2005M05-2019M12
Monetary policy					
Monetary policy shock	Jarociński and Karadi (2020)	0.08	0.32	140	2005M05-2016M12
Central bank info	Jarociński and Karadi (2020)	0.07	0.40	140	2005M05-2016M12
Financial & uncertainty					
Financial conditions	BBB spread residual	-0.04	0.61	176	2005M05-2019M12
Financial uncertainty	VIX residual (Bloom, 2009)	-0.05	0.48	176	2005M05-2019M12
	VSTOXX residual	-0.06	0.43	176	2005M05-2019M12
Policy uncertainty	Global EPU (Baker, Bloom, and Davis, 2016)	-0.07	0.37	176	2005M05-2019M12
Quarterly measures					
Fiscal policy	Euro area (Alloza, Burriel, and Pérez, 2019)	0.08	0.60	43	2005Q2-2015Q4
	Germany	0.24	0.12	43	2005Q2-2015Q4
	France	-0.03	0.85	43	2005Q2-2015Q4
	Italy	0.05	0.74	43	2005Q2-2015Q4
	Spain	0.14	0.36	43	2005Q2-2015Q4

Notes: The table shows the correlation of the carbon policy surprise series with a wide range of different shock measures from the literature, including global oil market shocks, monetary policy, financial and uncertainty shocks. ρ is the Pearson correlation coefficient, the p-value corresponds to the test whether the correlation is different from zero and n is the sample size.

B.2. More on aggregate effects

In this Appendix, I present some additional results pertaining to the analysis in Section 4 of the paper.

B.2.1. Internal instrument approach

A key advantage of the external instruments approach lies in its efficiency. However, this comes at the cost of assuming (partial) invertibility. If the invertibility assumption is not satisfied, this can lead to biased results (Li, Plagborg-Møller, and Wolf, 2021). To mitigate concerns about invertibility, I also present results from the internal instruments approach (Ramey, 2011; Plagborg-Møller and Wolf, 2019) which is robust to non-invertibility.

The results are shown in Figure B.2. The figure shows the responses from the internal instrument approach together with the external instrument baseline. We can see that the responses turn out to be very similar, both qualitatively and quantitatively. Only the estimated response of the two-year rate is somewhat less stable. We can also see that the internal instrument responses are much less precisely estimated as the confidence bands are significantly more dispersed. Overall, however, these findings suggest that the results are robust to relaxing the assumption of invertibility.

B.2.2. Local projection-instrumental variable approach

As discussed in the main text, I rely on VAR techniques for estimation because the sample is relatively short and VARs provide a parsimonious characterization of the data. However, as a robustness check, I have also tried to estimate the impulse responses using a local projections instrumental variable (LP-IV) approach à la Jordà, Schularick, and Taylor (2015) and Ramey and Zubairy (2018). To fix ideas, the dynamic causal effects, ψ_h^i, can be estimated from the following set of regressions:

$$y_{i,t+h} = \beta_h^i + \psi_h^i y_{1,t} + \boldsymbol{\beta}_h^{i\prime} \mathbf{x}_{t-1} + \xi_{i,t,h}, \tag{1}$$

using z_t as an instrument for $\Delta y_{1,t}$. Here, $y_{i,t+h}$ is the outcome variable of interest, $\Delta y_{1,t}$ is the endogenous regressor, $\mathbf{x}_{t-1}$ is a vector of controls, $\xi_{i,t,h}$ is a potentially serially correlated error term, and h is the impulse response horizon. I use the same controls as in the VAR. For inference, I follow again the lag-augmentation approach proposed by Montiel Olea and Plagborg-Møller (2020).

As the impacts of carbon policy are potentially quite persistent, we want to

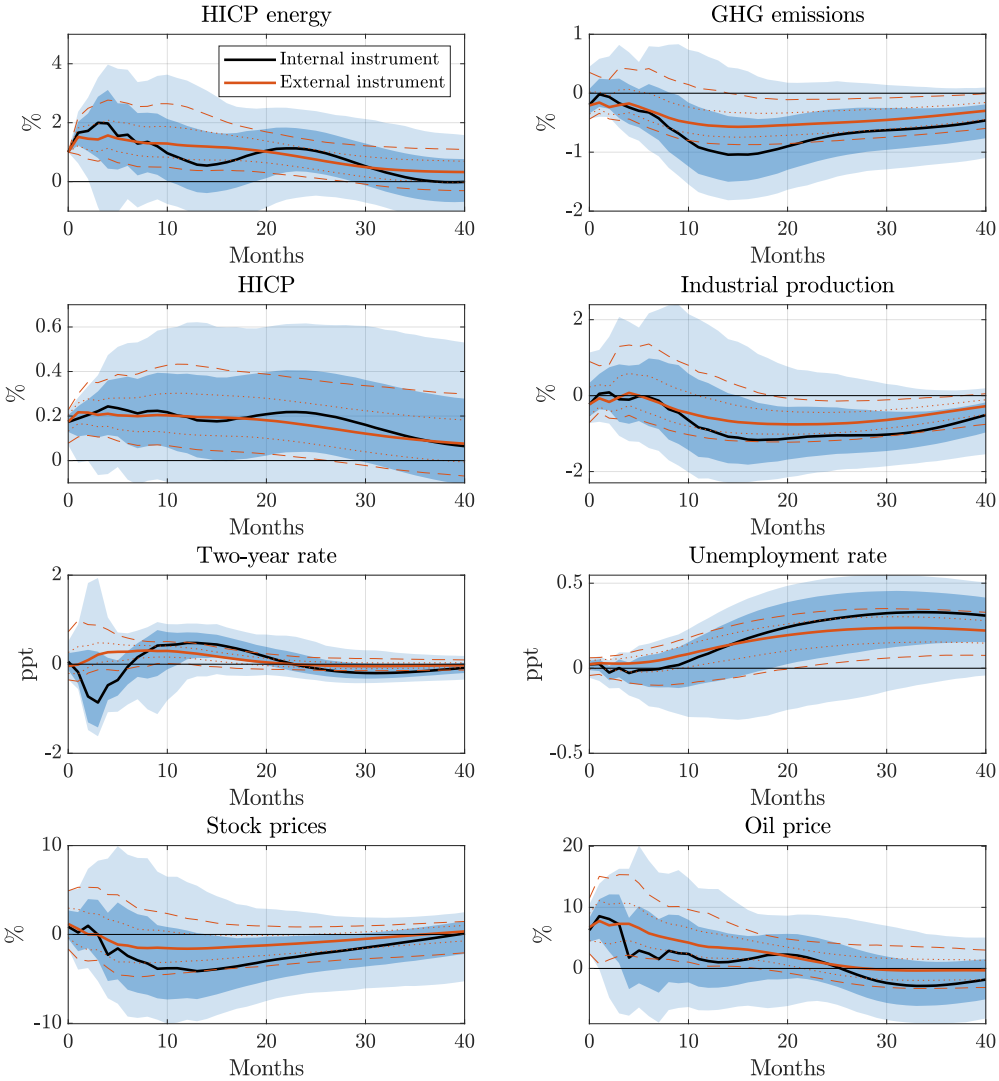


Figure B.2: Internal Versus External Instrument VAR

Notes: Impulse responses to a carbon policy shock, normalized to increase the HICP energy by 1 percent on impact. The solid dark and red lines are the point estimates for the internal instrument and the external instrument VAR, respectively, and the shaded areas / dashed lines are 68 and 90 percent confidence bands.

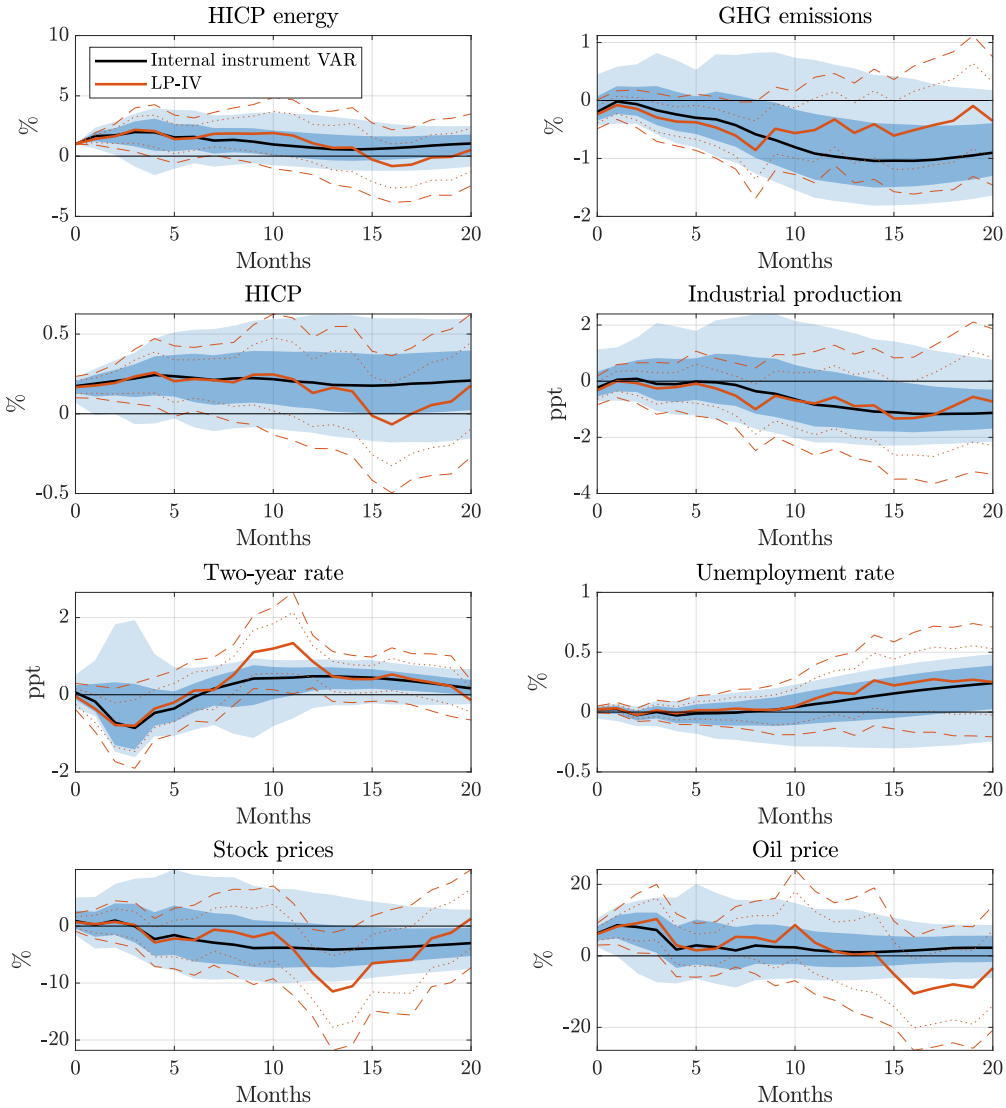


Figure B.3: Internal Instrument VAR Versus LP-IV

Notes: Impulse responses to a carbon policy shock, normalized to increase the HICP energy by 1 percent on impact. The solid dark and red lines are the point estimates for the internal instrument VAR and the LP-IV, respectively, and the shaded areas / dashed lines are 68 and 90 percent confidence bands.

look at the dynamic causal effects relatively far out. Given the short sample, this is challenging in the LP-IV framework, which does not use the parametric VAR restriction but estimates the effect by a distinct IV regression at each horizon h. Consequently, the number of observations available for estimation decreases with the impulse horizon. Against this background, I restrict the impulse horizon in the LP-IV regressions to 20 months.

Figure B.3 compares the responses obtained from the LP-IV approach to the ones from the internal instrument VAR. Recall that both approaches rely on the same invertibility-robust identifying restrictions but use different estimation techniques. We can see that the two approaches produce consistent results, especially at horizons up to one year.[3] At longer horizons the differences tend to be larger, however, the responses are also less precisely estimated.

B.2.3. Core versus headline HICP

In the paper, I document a significant and persistent increase in headline HICP. An important question that has also relevant implications for the conduct of monetary policy is how the shock transmits to core consumer prices. To this end, I re-estimate the model substituting headline for core HICP. Figure B.4 presents the response for core HICP together with the HICP headline and energy component from the baseline model. We can see that the response of core consumer prices is more muted and less precisely estimated. This illustrates that this is really a shock to relative prices. Reassuringly, all other responses from the model with core HICP are very similar to the baseline case.

[3]Note that this is despite the fact that we only control for 6 lags in both models.

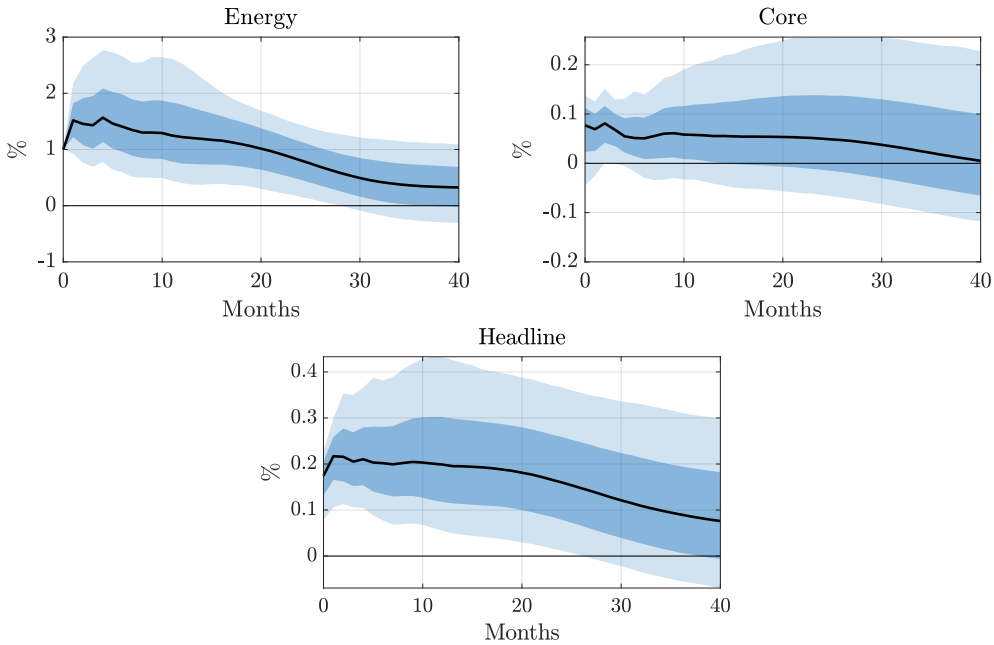


Figure B.4: Headline Versus Core HICP

Notes: Impulse responses of the headline, energy and core HICP to a carbon policy shock. The headline and energy indices are from the baseline model; the core response is from the model featuring core instead of headline HICP. The solid line is the point estimate and the dark and light shaded areas are 68 and 90 percent confidence bands, respectively.

B.2.4. Variance Decomposition

To better understand how carbon policy shocks have contributed to variations in macroeconomic and financial variables, I perform a variance decomposition exercise in addition to the historical decomposition presented in the paper. I do so both under the invertibility assumption maintained in the external instrument VAR as well as under weaker assumptions in the context of a general SVMA model, as proposed by Plagborg-Møller and Wolf (2020). In particular, I perform a standard forecast error variance decomposition in the SVAR and compute forecast variance ratios for the SVMA. The forecast variance ratio for variable i at horizon h is given by

$$FVR_{i,h} = 1 - \frac{\mathrm{Var}(y_{i,t+h} | \{y_\tau\}_{-\infty<\tau\leq t}, \{\varepsilon_{1,\tau}\}_{t<\tau<\infty})}{\mathrm{Var}(y_{i,t+h} | \{y_\tau\}_{-\infty<\tau\leq t})}, \tag{2}$$

and measures the reduction in the econometrician's forecast variance that would arise from being told the entire path of future realizations of the shock of interest. Plagborg-Møller and Wolf (2020) show that this statistic is interval-identified under the assumption that a valid instrument is available. Under the assumption of recoverablity, the ratio is point-identified by the upper bound.

The results are shown in Table B.3. We can see that carbon policy shocks have contributed meaningfully to historical variations in the variables of interest. Under the invertibility assumption (Panel A), they account for about 30 percent of the variations in energy prices and around 10 percent of the short-run variations in emissions, which goes up to over 20 percent at the 3 year horizon. Turning to the macroeconomic variables, we can see that they explain a substantial part of variations in the HICP, especially at shorter horizons, and a non-negligible fraction of the variations in industrial production and the unemployment rate at longer horizons. The shocks explain less of the variations in the two-year rate and stock prices but can account for about 20 percent of the variation in oil prices. The forecast variance ratios in Panel B, which dispense from the assumption of invertibility, paint a similar picture.

Table B.3: Variance Decomposition

h	HICP energy	Emissions	HICP	IP	Two-year rate	Unemp. rate	Stock prices	Oil price
Panel A: Forecast variance decomposition (SVAR-IV)								
6	0.38	0.12	0.46	0.02	0.04	0.05	0.02	0.22
	[0.03, 0.49]	[0.02, 0.42]	[0.04, 0.57]	[0.01, 0.30]	[0.01, 0.24]	[0.00, 0.33]	[0.01, 0.31]	[0.01, 0.33]
12	0.31	0.18	0.32	0.05	0.08	0.08	0.03	0.20
	[0.03, 0.41]	[0.02, 0.43]	[0.03, 0.46]	[0.02, 0.33]	[0.01, 0.22]	[0.01, 0.37]	[0.01, 0.33]	[0.02, 0.31]
24	0.30	0.22	0.23	0.13	0.08	0.18	0.04	0.20
	[0.03, 0.38]	[0.02, 0.39]	[0.02, 0.39]	[0.02, 0.34]	[0.02, 0.21]	[0.01, 0.43]	[0.01, 0.31]	[0.02, 0.27]
36	0.28	0.20	0.18	0.16	0.08	0.23	0.04	0.16
	[0.03, 0.35]	[0.02, 0.36]	[0.02, 0.35]	[0.02, 0.33]	[0.02, 0.21]	[0.01, 0.44]	[0.02, 0.31]	[0.02, 0.24]
Forecast variance ratio (SVMA-IV)								
6	0.04, 0.21	0.01, 0.06	0.04, 0.21	0.00, 0.01	0.03, 0.14	0.00, 0.01	0.00, 0.02	0.01, 0.08
	[0.01, 0.39]	[0.00, 0.25]	[0.01, 0.40]	[0.00, 0.17]	[0.01, 0.37]	[0.00, 0.15]	[0.00, 0.19]	[0.01, 0.24]
12	0.03, 0.15	0.03, 0.15	0.03, 0.15	0.01, 0.03	0.03, 0.18	0.00, 0.01	0.01, 0.04	0.01, 0.06
	[0.01, 0.36]	[0.00, 0.45]	[0.01, 0.39]	[0.00, 0.27]	[0.01, 0.41]	[0.00, 0.21]	[0.00, 0.27]	[0.01, 0.26]
24	0.02, 0.13	0.04, 0.23	0.02, 0.11	0.02, 0.10	0.03, 0.19	0.02, 0.09	0.01, 0.06	0.01, 0.06
	[0.01, 0.36]	[0.00, 0.50]	[0.00, 0.39]	[0.00, 0.32]	[0.02, 0.38]	[0.00, 0.33]	[0.00, 0.31]	[0.01, 0.26]
36	0.02, 0.12	0.04, 0.21	0.02, 0.09	0.02, 0.13	0.04, 0.20	0.03, 0.14	0.01, 0.06	0.01, 0.06
	[0.01, 0.33]	[0.00, 0.46]	[0.00, 0.36]	[0.00, 0.32]	[0.02, 0.38]	[0.00, 0.38]	[0.01, 0.31]	[0.01, 0.26]

Notes: The table shows the variance decomposition at horizons ranging from 6 months to 4 years. Panel A includes the forecast error variance decomposition from the external instrument VAR, Panel B shows the identified set for the forecast variance ratio. Bootstrapped 90% confidence intervals are reported in brackets.

B.2.5. Financial conditions and uncertainty

To better understand how the shock transmits to the economy, I have also looked at the responses of indicators for financing conditions and financial uncertainty, see Figure B.5. However, as can be seen from the responses these variables do not appear to play a dominant role in the transmission of the carbon policy shock.

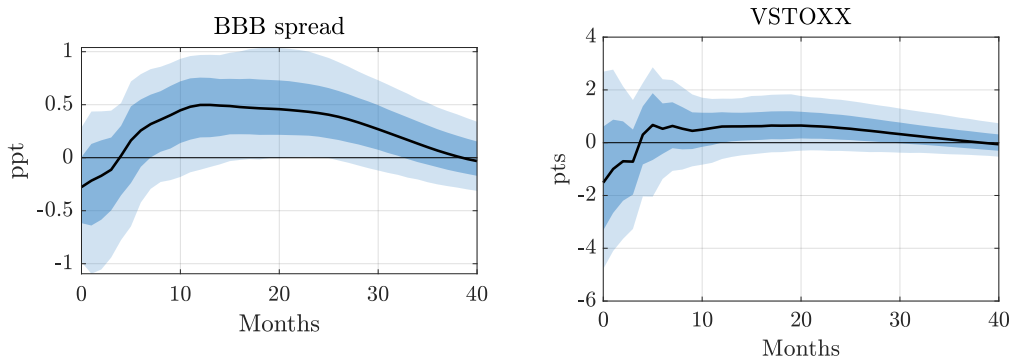


Figure B.5: Financial Conditions and Uncertainty

Notes: Impulse responses of financial conditions, as proxied by the BBB bond spread, and the VSTOXX index as a measure of financial uncertainty.

B.2.6. Aggregate effects for the UK

Because of data availability, the household-level analysis is carried out for the UK. As a validating exercise, I have verified that the aggregate effects on the UK, as measured by real GDP, consumption and investment, are comparable to the EU level responses, see Figure B.6.

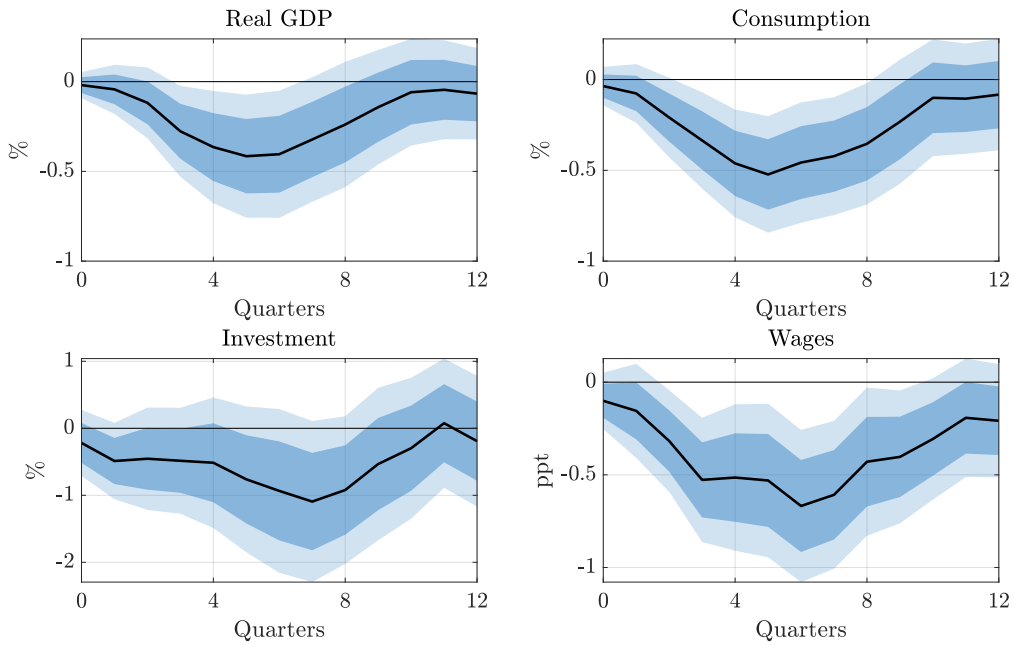


Figure B.6: Effect on GDP, Consumption, Investment and Wages in the UK

Notes: Impulse responses of a selection of quarterly variables estimated using local projections on the carbon policy shock. The responses are normalized to have the same peak effect on HICP energy as in the baseline model.

B.3. More on heterogeneous effects

In this Appendix, I present some additional results pertaining to Section 5 on the heterogeneous effects of carbon pricing in the paper.

B.3.1. Further descriptive statistics

Figure B.7 compares the empirical distribution of age and total expenditure for the three income groups. We can see that the groups are comparable in terms of their age distribution. As expected, higher income groups tend to have higher expenditure but there is also more within group variation.

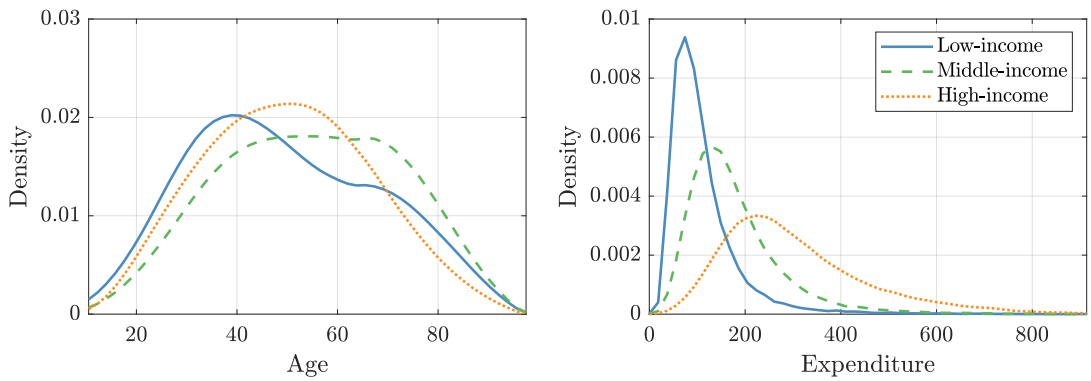


Figure B.7: Empirical Distribution of Age and Total Expenditure in the LCFS

Notes: The figure shows the empirical probability distribution of age and total expenditure (excl. housing) for all three income groups. The distributions are estimated using an Epanechnikov kernel.

Figure B.8 depicts the evolution of different households characteristics, including age, education and housing tenure, over time. We can see that there are some trends in these variables, however, they are rather slow-moving and thus unlikely to confound potential heterogenities in the household responses to carbon policy shocks, which exploit variation at a much higher frequency.

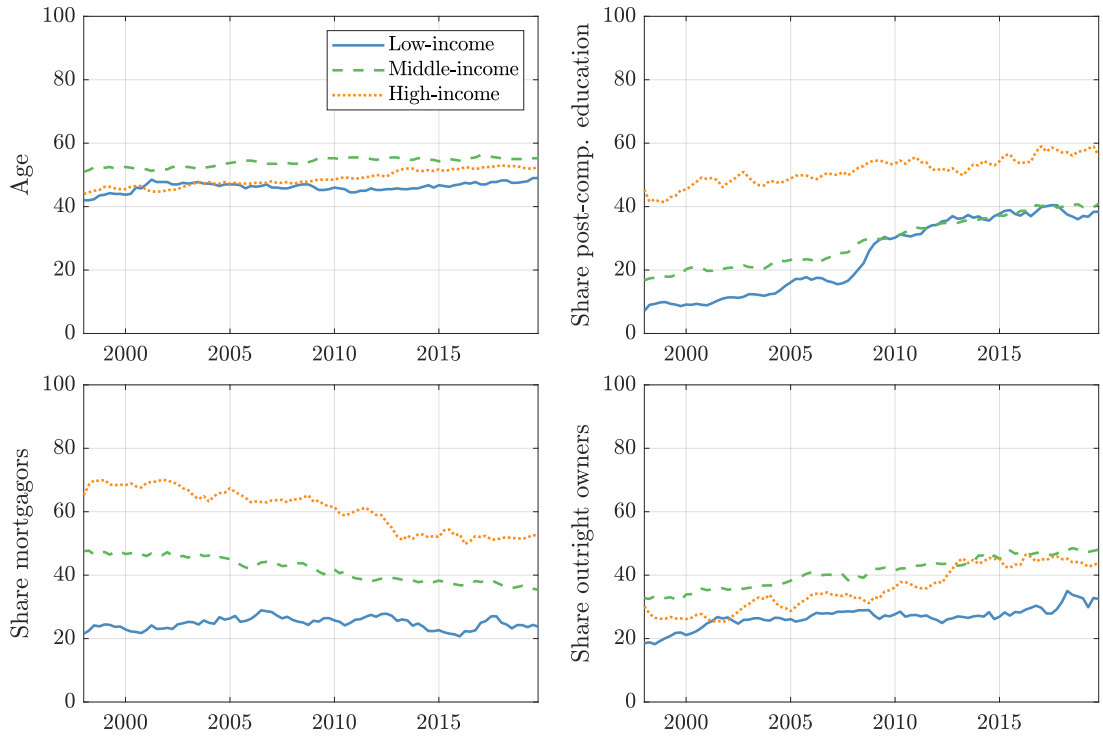


Figure B.8: Evolution of Household Characteristics by Income Group

Notes: The figure shows the evolution of age, education, and housing tenure status over time by income group.

B.3.2. Aggregate expenditure responses

Before studying at the heterogeneous expenditure responses by income group, I look at the aggregate expenditure responses as a validating exercise. The results are shown in Figures B.9. We can see that the response of aggregated expenditure from household micro data is very similar to the consumption response from national statistics – both in terms of shape and magnitude. This supports the notion that the micro data is indeed representative for the macroeconomy. For completeness, I also report the aggregated responses for different expenditure categories.

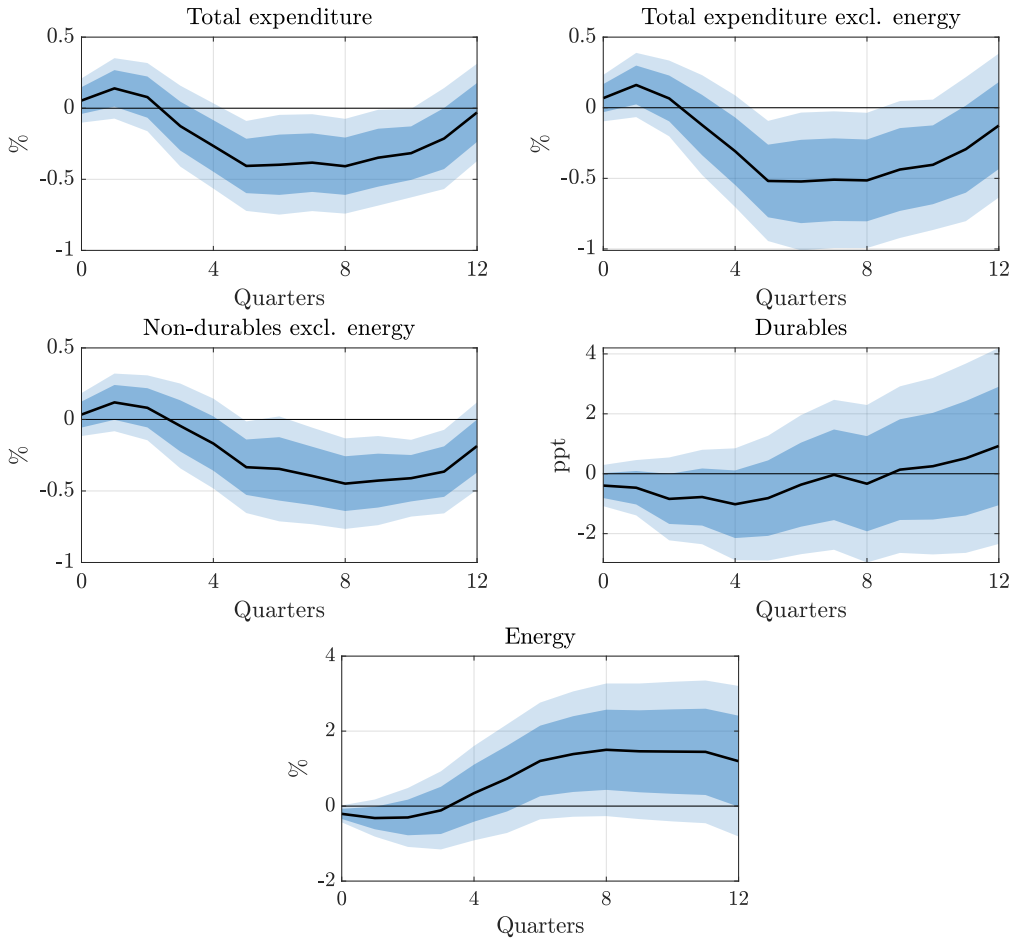


Figure B.9: Aggregate Expenditure Responses

B.3.3. Smoothing impulse responses

In the LCFS, households interviewed at time t are typically asked to report expenditure over the previous three months (with the exception of non-durable consumption which refers to the previous two weeks). To eliminate some of the noise inherent in survey data, I smooth the expenditure and income measures with a backward-looking (current and previous three quarters) moving average, as in Cloyne, Ferreira, and Surico (2020). However, as shown in Figure B.10, the results are very similar when using the raw series instead, even though the responses become more jagged and imprecise, or by using smooth local projections as proposed by Barnichon and Brownlees (2019).

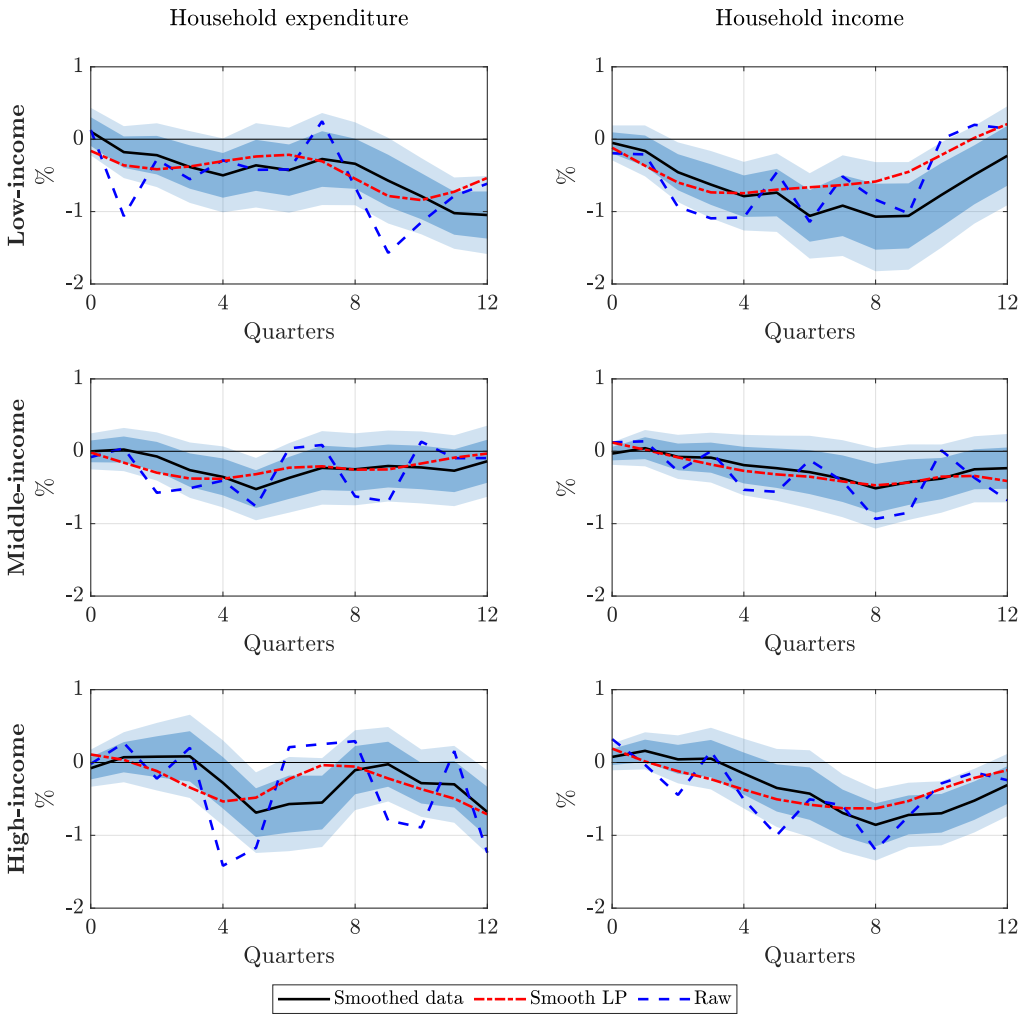


Figure B.10: Sensitivity with Respect to Smoothing of Responses

Notes: Impulse responses of total expenditure excluding housing and current total disposable household income by income group, computed using simple backward-looking moving average (baseline), smooth local projections (red dotted line), and unsmoothed (blue dashed line).

B.3.4. Group differences

In the main text, we document pervasive heterogeneity in the expenditure and income responses by household income group. Another important question is whether these differences are statistically significant. To this end, I estimate the responses of the group differences in expenditure and income, in particular low-income versus middle-income and low-income versus high-income. The responses are shown in Figure B.11. We can see that low-income households display a significantly stronger fall in income and expenditure than higher-income households. Thus, the group differences are not only economically but also statistically significant.

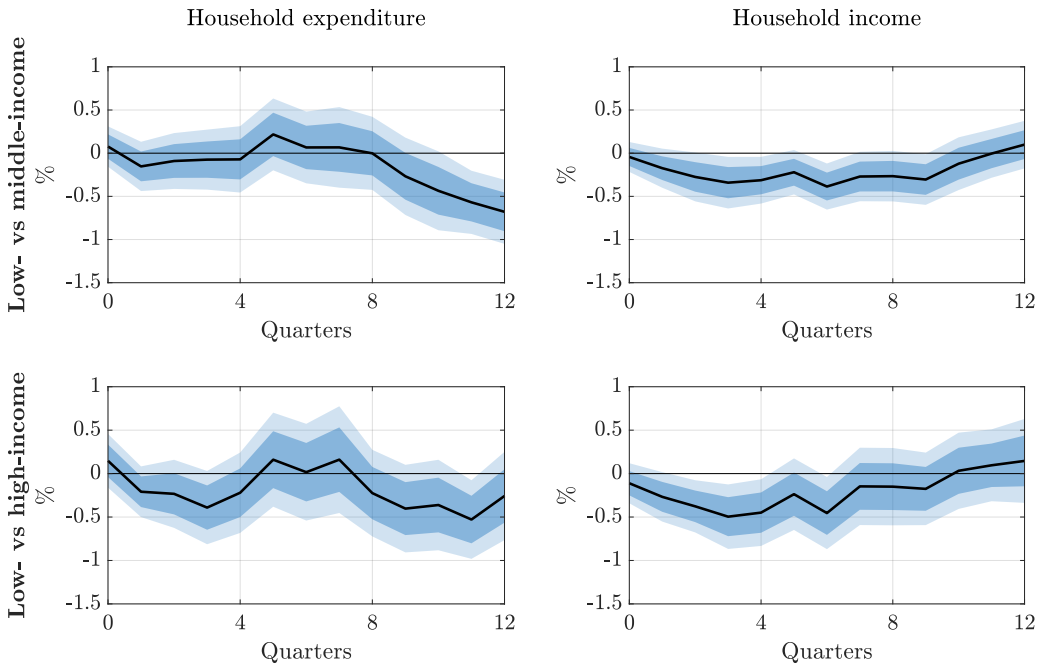


Figure B.11: Group differences in Expenditure and Income Responses

B.3.5. Robustness concerning grouping

To mitigate concerns about endogenous changes in the grouping variable, I look at the responses of current and normal disposable income in Figure B.12. We can see that both variables are rather slow-moving. Current income starts to fall significantly after about a year. In contrast, the response of normal disposable income moves less and is insignificant, supporting its validity as a grouping variable.

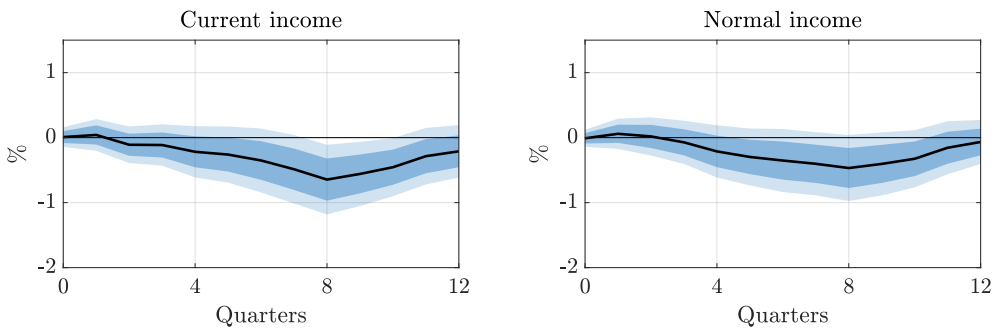


Figure B.12: Responses of Current and Normal Income

As discussed in the main text, the normal income variable can be thought of as a proxy for permanent income. As a robustness check, I compute estimates for permanent income from a Mincerian-type regressions. Specifically, I use age, education, ethnicity, sex, martial status, occupation, the source of the main household income, as well as interactions between age and education, and between age

and sex as predictors, as in Alves et al. (2020). Figure B.13 shows the responses by permanent income group. We can see that the results turn out to be robust.

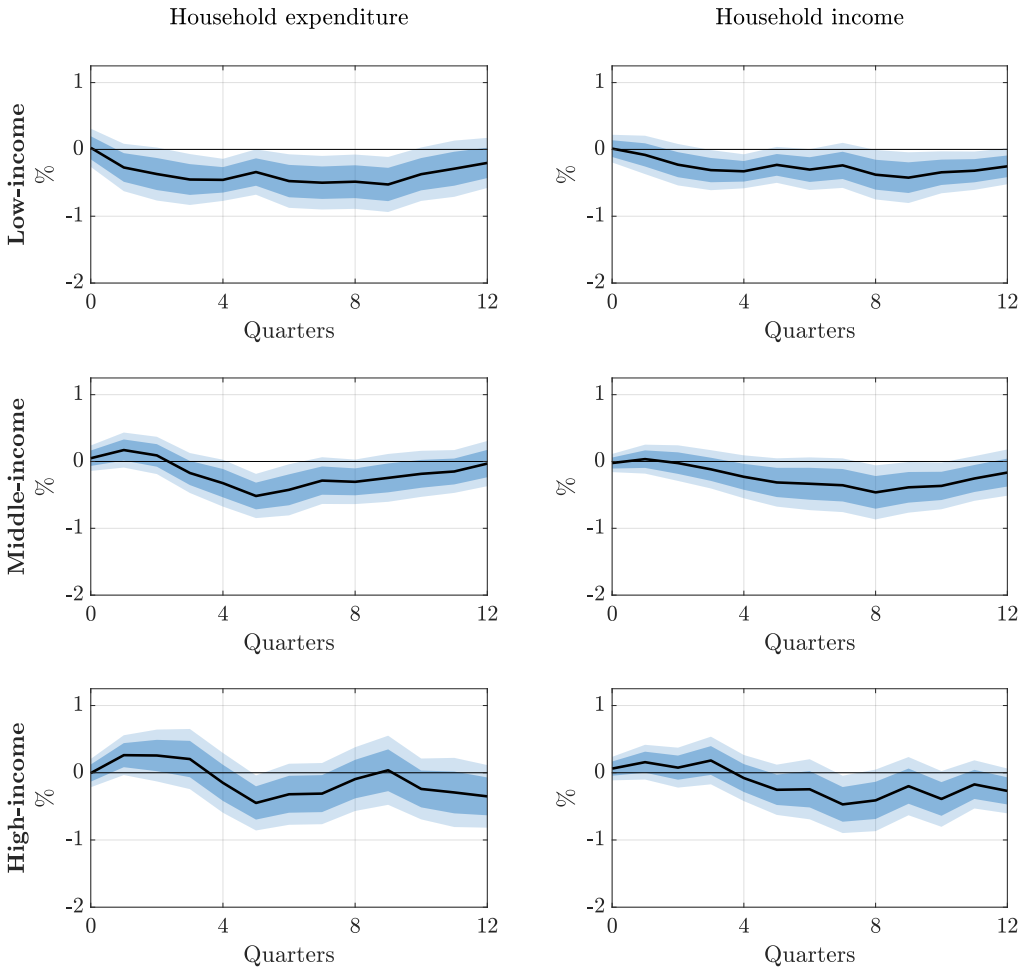


Figure B.13: Expenditure and Income Responses by Permanent Income

Notes: Impulse responses of total expenditure excluding housing and current total disposable household income by permanent income, estimated using a Mincerian-type regression using age, education, ethnicity, sex, martial status, occupation, the source of the main household income, as well as interactions between age and education, and between age and sex (bottom 25 percent, middle 50 percent, top 25 percent).

B.3.6. Selection

To mitigate concerns about selection, I use a number of different grouping variables, including age, education and housing tenure. From Figures B.14-B.16, we can see that none of these alternative grouping variables can account for the patterns uncovered for income, suggesting that we are not spuriously picking up differences in other household characteristics. Similarly, the uncovered heterogeneity can also not be accounted for by occupation, sex and region. These results are available from the author upon request.

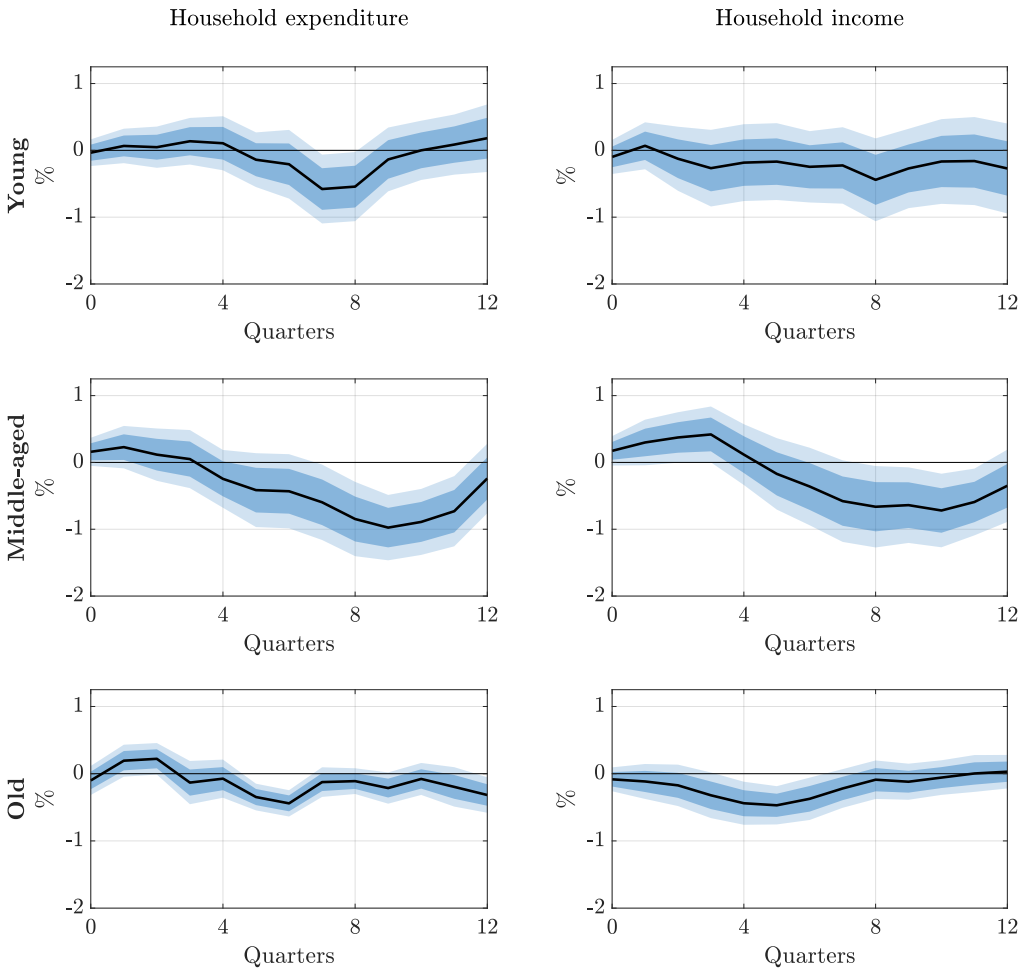


Figure B.14: Household Expenditure and Income Responses by Age Group

Notes: Impulse responses of total expenditure excluding housing and current total disposable household income for young (bottom 33 percent), middle-aged (middle 33 percent) and older households (top 33 percent), based on the age of the household head.

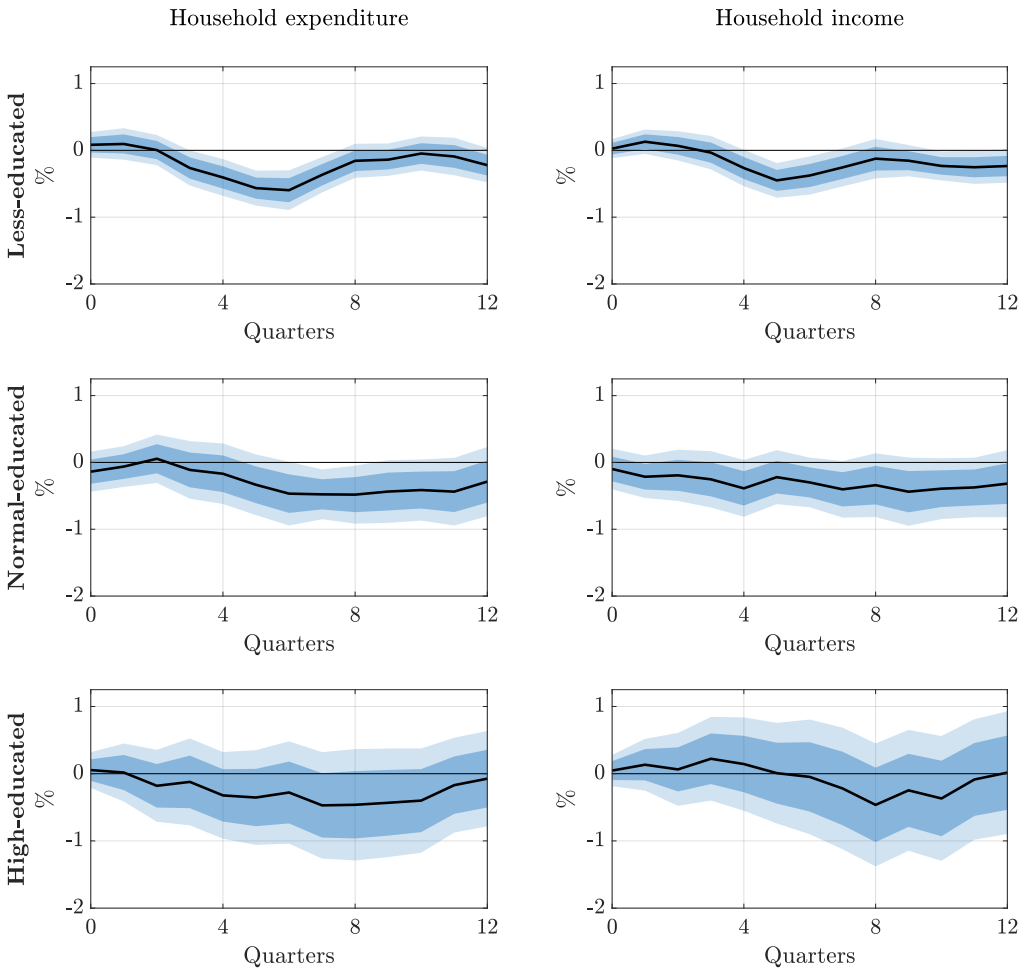


Figure B.15: Household Expenditure and Income Responses by Education Status

Notes: Impulse responses of total expenditure excluding housing and current total disposable household income for less educated, normally educated and well educated households. Education status is proxied by the highest age a household member has completed full-time education and the three groups are below 16 years, between 17 and 18 years (compulsory education), and 19 years or above (post-compulsory).

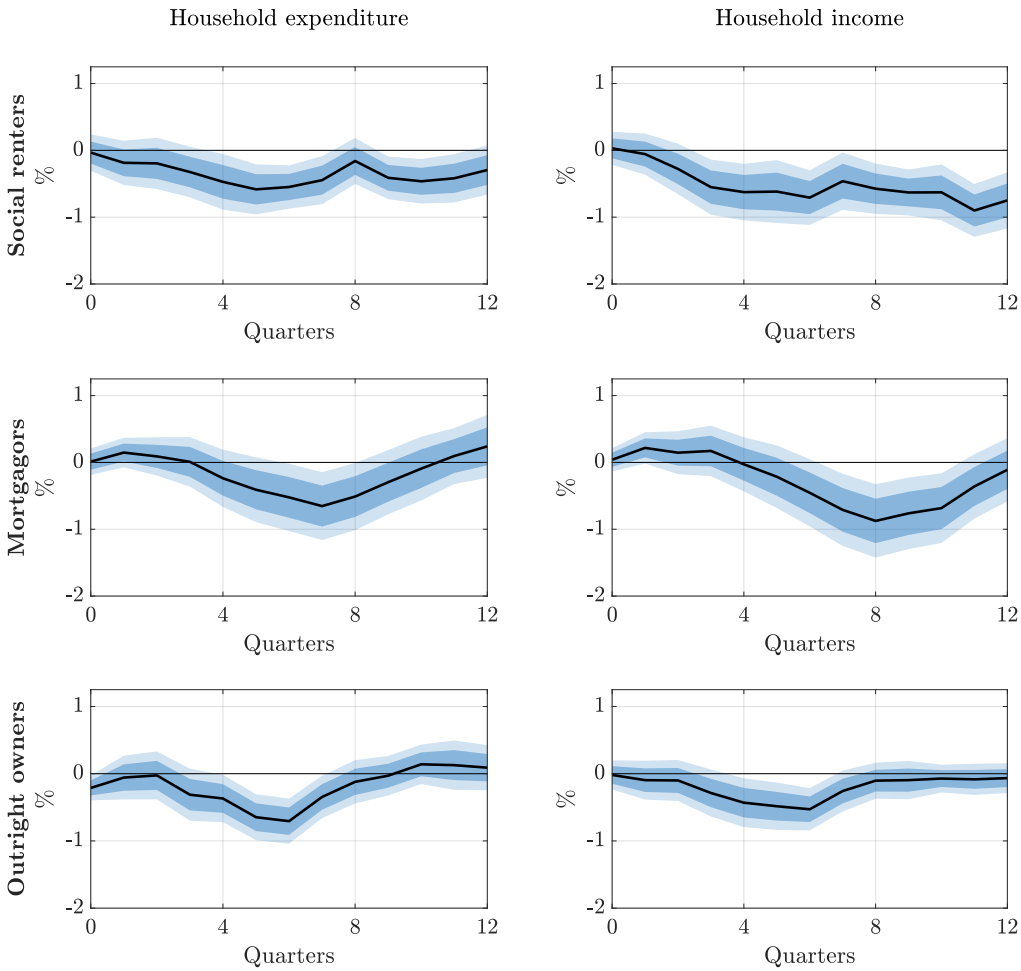


Figure B.16: Household Expenditure and Income Responses by Housing Tenure

Notes: Impulse responses of total expenditure excluding housing and current total disposable household income for social renters, mortgagors and outright owners.

B.3.7. What drives the income response?

To understand what is driving the heterogeneity in the income responses, we study how the labor income responses vary by sector of employment using data from the LFS. To this end, I grouped sectors according to their SIC 2003 sections by their energy intensity and their "demand sensitivity", i.e. how much sectoral labor income changes after changes in aggregate income. The data on energy intensities is from the ONS. The demand sensitivity is proxied by the elasticity of sectoral labor income to aggregate labor income, using sectoral data from the LFS and wage data from national accounts. Similar results are obtained when estimating the elasticity with respect to the unemployment rate. Table B.4 shows the data on sectoral energy intensity and estimated demand sensitivity together with the resulting classification. I define high energy intensive sectors as sectors

Table B.4: Sectors by Energy Intensity and Demand Sensitivity

Panel A: Energy intensity and estimated demand sensitivity

Sectors		Energy intensity (TJ/£m)	Demand sensitivity ($\varepsilon_u y_i$)
A-B:	Agriculture, forestry and fishing	11.4	0.43
C,E:	Mining and quarrying; energy, gas and water	12.8	0.16
D:	Manufacturing	11.6	0.44
F:	Construction	2.6	0.52
G-H:	Wholesale and retail trade; hotels and restaurants	3.0	0.51
I:	Transport, storage and communication	9.4	0.19
J-K:	Banking, finance and insurance	0.7	0.41
L-N:	Public admin, education and health	1.3	0.35
O-Q:	Other services	1.1	0.72

Panel B: Sector classification

Group	Sectors	SIC sections
High energy intensity	Agriculture, forestry, and fishing; mining and quarrying; manufacturing; electricity, gas and water supply (utilities); transport, storage and communications	A-E, I
Lower energy intensity	Construction; Wholesale and retail trade; Hotels and restaurants; Financial intermediation; Real estate, renting and business; Public administration and defense; Education; Health and social work; Other community, social and personal services	F-H, J-Q
High demand sensitivity	Construction; Wholesale and retail trade; Hotels and restaurants; Other community, social and personal services	F-H, O-Q
Lower demand sensitivity	Agriculture, forestry, and fishing; mining and quarrying; manufacturing; electricity, gas and water supply (utilities); transport, storage and communications; Financial intermediation; Real estate, renting and business; Public administration and defense; Education; Health and social work	A-E, J-N

Notes: The sectors are grouped based on SIC 2003 sections. Note that the grouping is not perfect, as the LFS only has information on groups of sections over the entire sample of interest. The data on the energy intensity by sector from 1999-2019 is from the ONS.

with an energy intensity above 5 and high demand sensitive sectors as sectors with a demand sensitivity in excess of 0.5. Choosing the threshold involves some judgment. As a robustness check, I have excluded/included the sectors closest to the two thresholds for both groupings. The results turn out to be not sensitive to the precise level of the threshold.

Finally, another source of heterogeneity in the income response is the income composition. To better understand this, I study the responses of labor earnings and financial income. We can see that the earnings of low-income households fall more promptly and significantly than for higher-income households, consistent with the results on total income. On the other hand, the financial income of low- and middle-income households barely shows a response, reflecting the fact that these households own very little financial assets. In contrast, high-income households experience a temporary fall in their financial income in the short run, which however subsequently reverts (consistent with the stock market response).

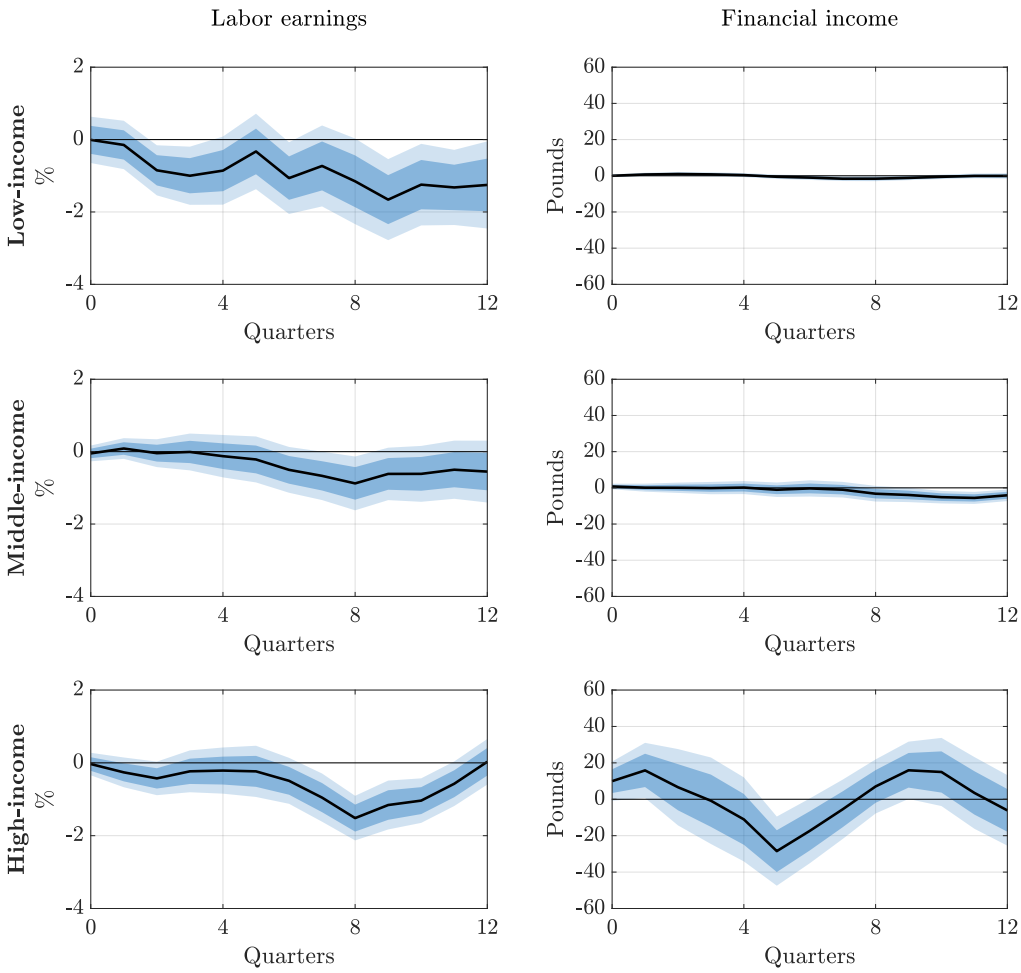


Figure B.17: Responses of Earnings and Financial Income

Notes: Impulse responses of labor earnings (wages from main occupation) and financial income (interest, dividend, rents) by income group (bottom 25 percent, middle 50 percent, top 25 percent).

B.3.8. External validity

To mitigate concerns regarding external validity, I confirm the main results on the heterogeneity in household expenditure by income group using data for Denmark and Spain. As can be seen from Figure B.18, the expenditure response turns out to be significant and persistent for low-income households, while high-income households are much less affected. These findings confirm the results for the UK, supporting the external validity of the results.

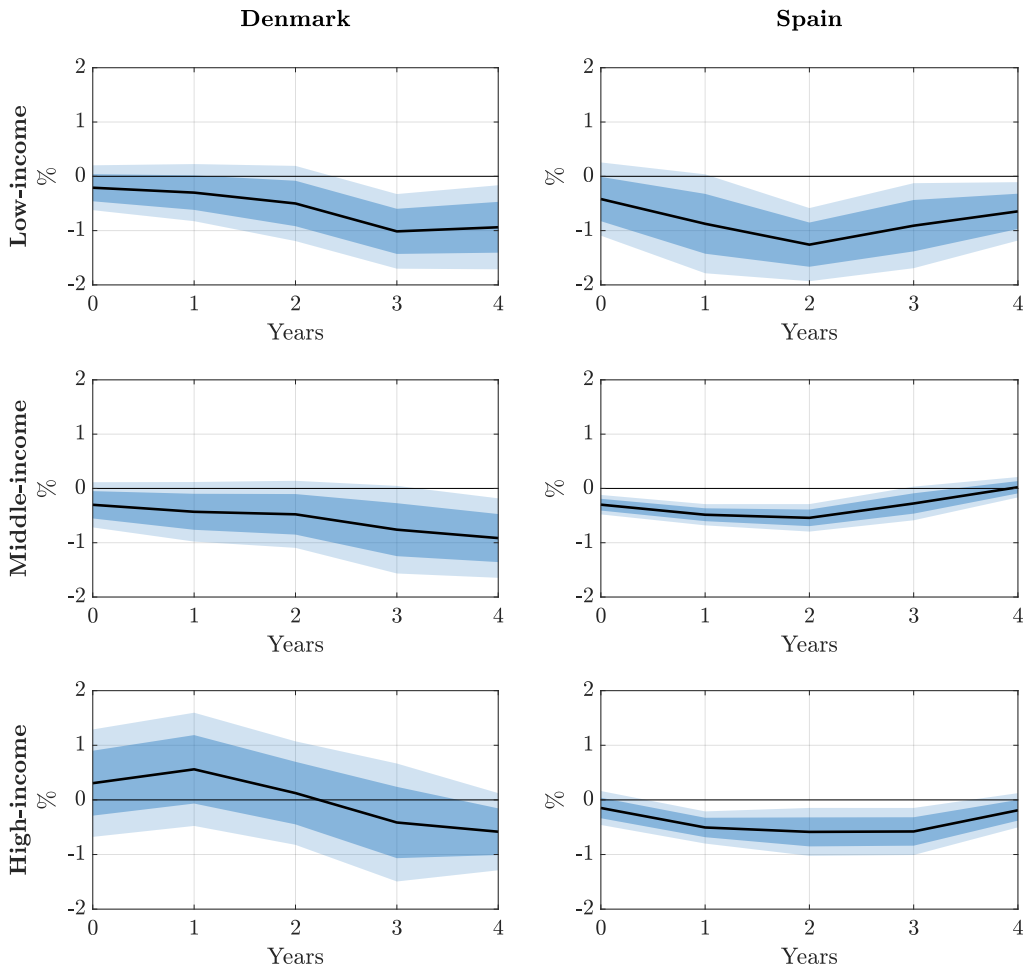


Figure B.18: Expenditure by Income Group for Other European Countries

Notes: Impulse responses of total expenditure for low-income, middle-income and high-income households in Denmark and Spain. The Danish data are from the Danish household budget survey (HBS) available for 1999-2019, accessed via the StatBank Denmark database, and expenditure is grouped by total annual income (under 250K DKK, 250-999K DKK, 1000K DKK or over). The Spanish data are from the Spanish HBS available for 2006-2019, accessed via the INE website, and expenditure is grouped by regular net monthly household income (under 1000 euros, 1000-2499 euros, 2500 euros or over).

B.3.9. Attitudes towards climate policy

As discussed in the paper, public opposition can be an impediment for climate policy. Thus, it is interesting to see how carbon pricing affects the public attitude towards climate policy. To analyze this question, I use data from the British social attitudes (BSA) survey. The BSA is an annual survey that asks about the attitudes of the British population towards a wide selection of topics, ranging from welfare to genomic science. The BSA is used to inform the development of public policy and is an important barometer of public attitudes. Some of the questions in the BSA are repeated over time and thus, it is possible to analyze how certain attitudes have changed over time.

To proxy the public attitude towards climate policy, I rely on a question from the transportation module of the survey, which asks about the attitude towards environmentally-motivated fuel taxes. In particular, the question asks whether the respondent agrees with the following statement: "For the sake of the environment, car users should pay higher taxes". The BSA also includes information about the income of the respondent, thus it is possible to analyze how the attitudes of different income groups have evolved. Figure B.19 shows how the attitude towards climate policy has changed among low- and higher-income households. We can see that the support of climate policy has remained relatively stable at moderate levels for a large part of the sample. In the early to middle 2010s, the support started increasing for higher-income households. In contrast, the support of low-income households has remained stable until the end of the sample.

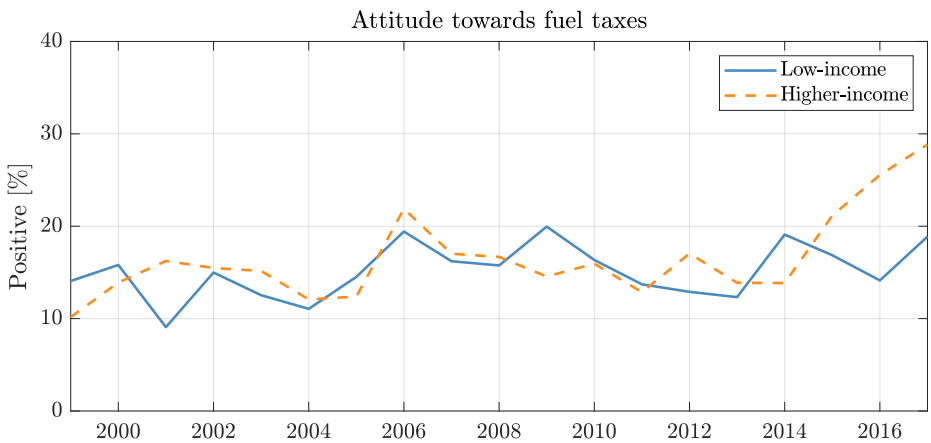


Figure B.19: Public support for climate policy by income group

Notes: The figure shows the evolution of the attitude towards climate policy by income group, as proxied by the share of households in the British social attitudes survey that agree to the following statement: "For the sake of the environment, car users should pay higher taxes".

B.4. Additional results from heterogeneous-agent climate-economy model

In this appendix, we present some additional results from the heterogeneous-agent climate-economy model. Figure B.20 shows the response of emissions under the different carbon revenue redistribution schemes. We can see that emissions fall by somewhat less when redistributing revenues than under the baseline case when all revenues accrue to the savers but importantly, the consumption response is dampened significantly more (by a factor close to 45 percent). This suggests that there may be a trade-off that policy makers could exploit. The intuition behind this result is that low-income households' energy demand is particularly inelastic and they make up only a small share of aggregate emissions to start with.

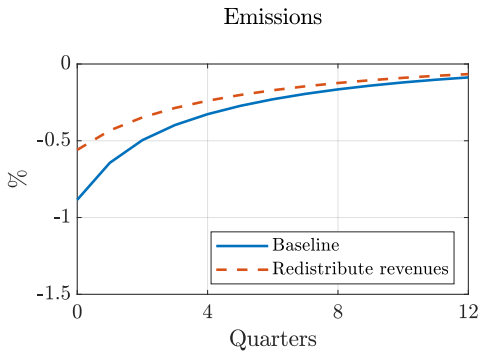


Figure B.20: Emissions Response

As discussed in the main text, monetary policy plays an important role in the transmission of the policy. After a carbon policy shock leading to an increase in energy prices, monetary policy leans against the inflationary pressures by increasing interest rates. This in turn leads to a further fall in consumption and investment. Figure B.21 shows the impulse responses under two different monetary policy rules. As the baseline, we assume that monetary policy targets headline inflation. As an alternative, we consider a rule where monetary policy targets core inflation. We can see that the effects on consumption and income are attenuated significantly when monetary policy targets core instead of headline inflation.

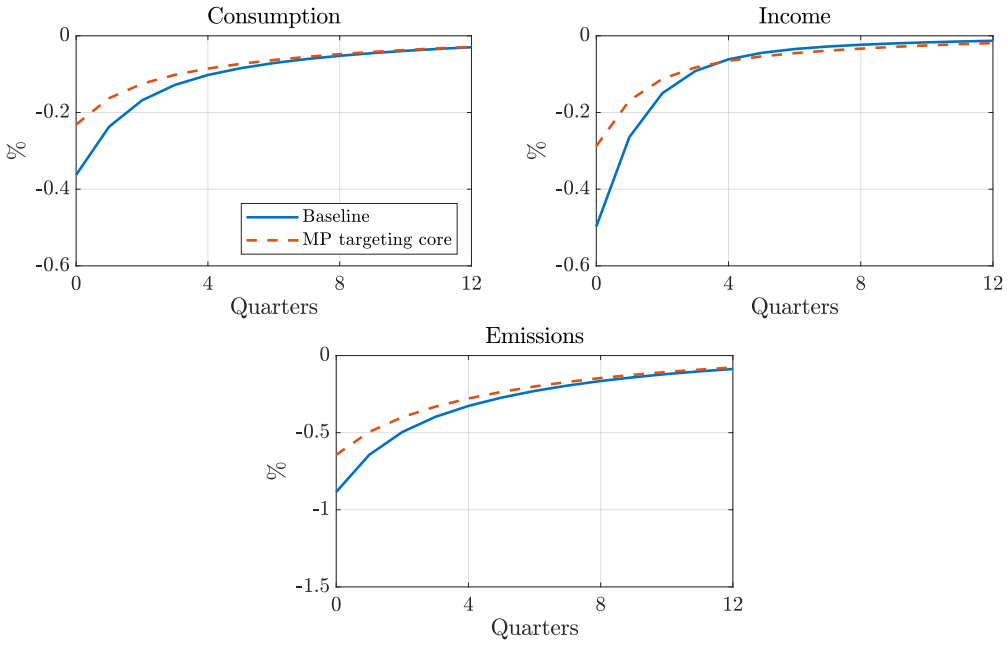


Figure B.21: The Role of Monetary Policy

Household heterogeneity also plays an important role for the magnitudes of the responses. In particular, heterogeneity in MPCs linked to heterogeneity in energy shares and income incidence can amplify the responses further. This is illustrated in Figure B.22, which compares the responses of the heterogeneous agent to the corresponding representative agent version of the model.

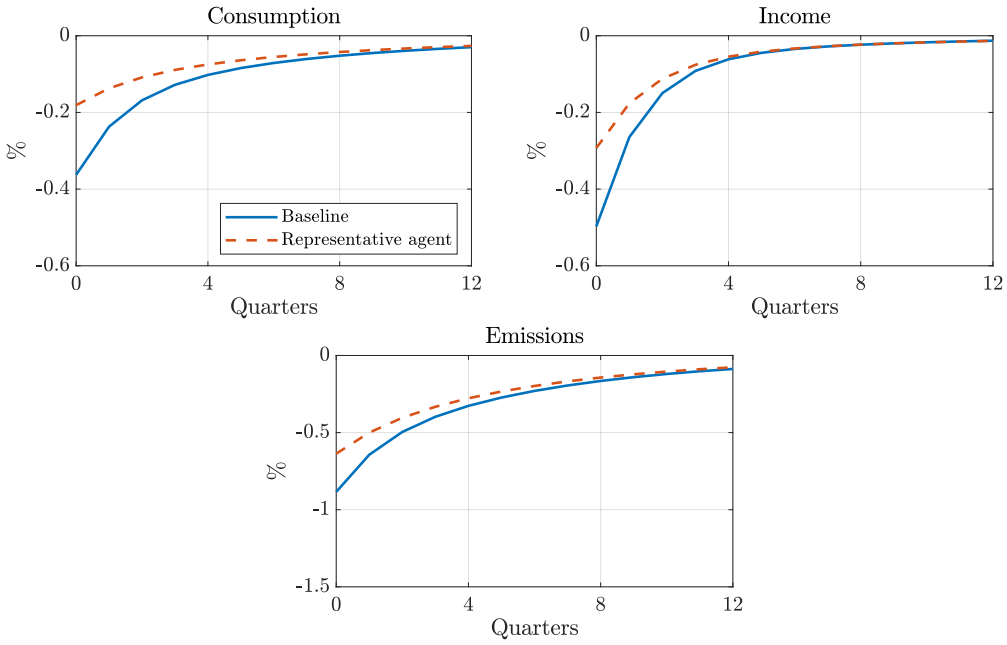


Figure B.22: Heterogeneity Versus Representative Agent

To get a better understanding of how much the heterogeneity matters for the direct and indirect channels we identify, we perform a decomposition. In particular, we compare four different scenarios: (i) a model where there is no heterogeneity in income incidence and energy share (this is achieved by perfectly redistributing income over the cycle and calibrating the energy share for H and S to the same level), (ii) a model with equal incidence but heterogeneity in energy shares, (iii) a model with unequal incidence and no energy share heterogeneity, and (iv) our baseline case with both heterogeneities. From Figure B.23, we can see that the heterogeneity in income incidence turns out to be crucial, accounting for the bulk of the amplification of the aggregate consumption response. This can be seen from the fact that the model with unequal incidence is already very close to the baseline with heterogeneous energy shares and income incidence.

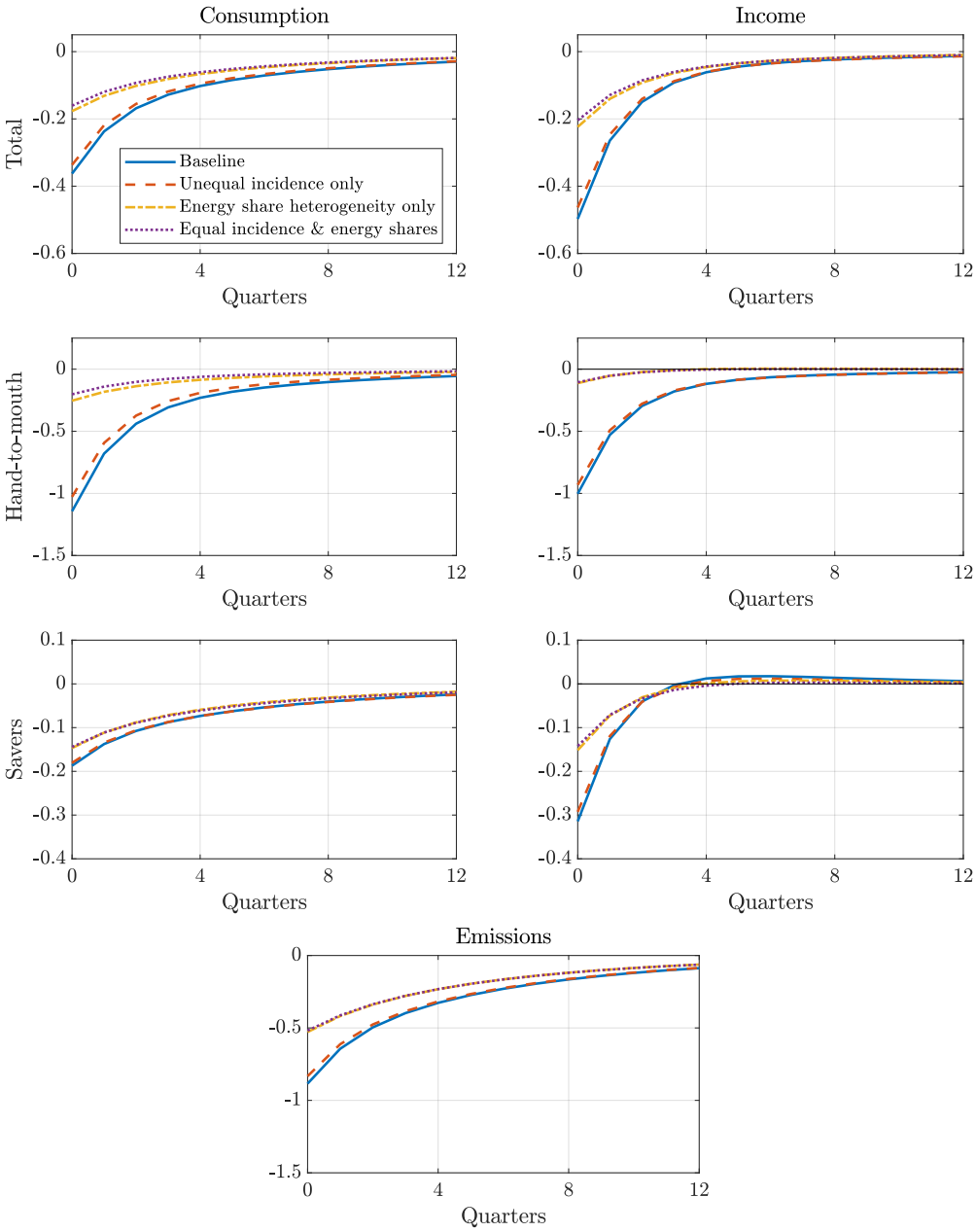


Figure B.23: Role of Unequal Income Incidence and Energy Share Heterogeneity

C. Sensitivity Analysis

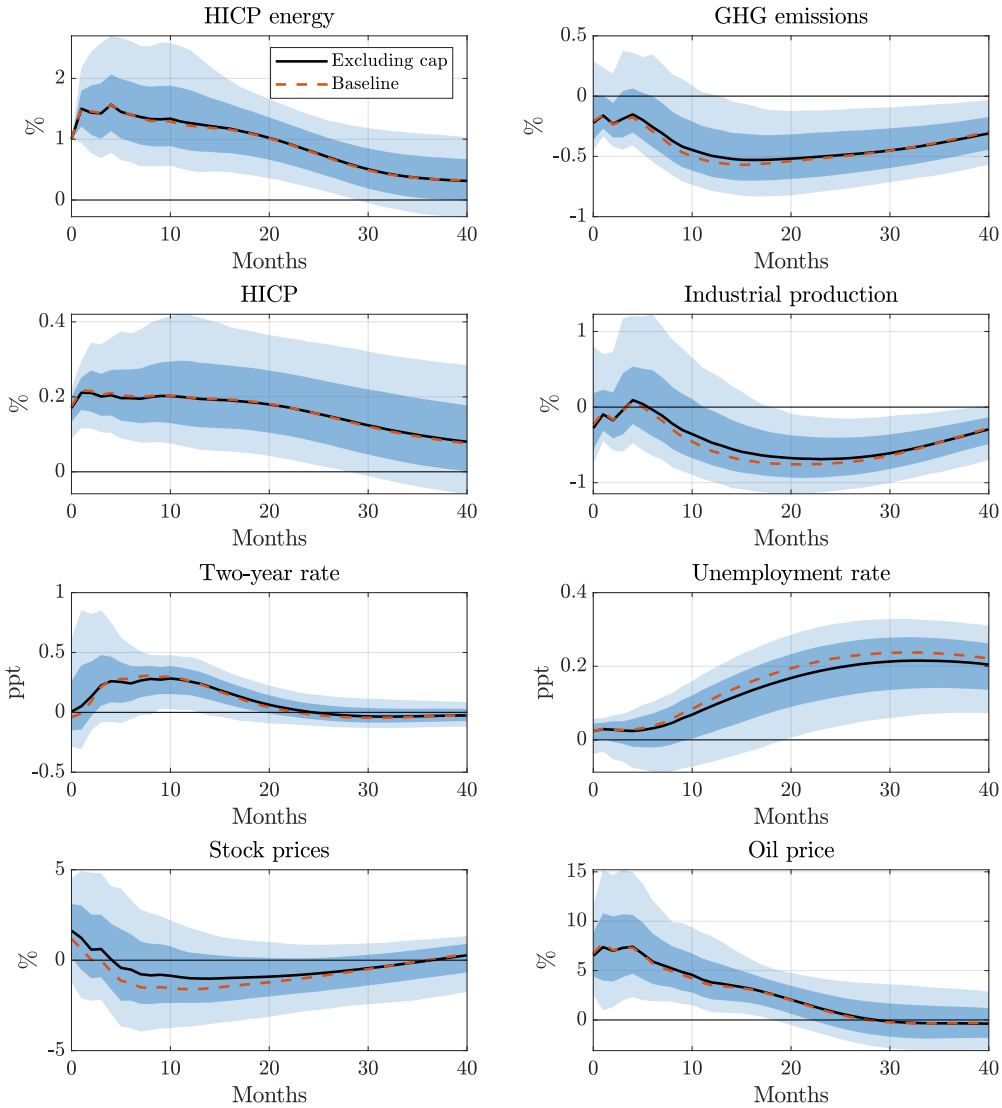
In this Appendix, I perform a number of robustness checks on the identification strategy and the empirical specification used to isolate the carbon policy shock, as discussed in Sections 2-3 of the paper. Throughout, I report the point estimate as the solid black line and 68 and 90 percent confidence bands as dark and light shaded areas, respectively.

C.1. Instrument construction

Selection of relevant events. A crucial choice in the high-frequency event study approach concerns the selection of relevant events. For the exclusion restriction to be satisfied, the events should only release information about the supply of emission allowances and not about other factors such as macroeconomic or geopolitical news. To this end, I have not included broader events such as the Paris agreement or other COP meetings but limited the analysis to specific events in the European carbon market. The most obvious candidates are events about the free allocation and auctioning of emission allowances. I have also included events on the overall cap in the carbon market as well as events about international credits.

Because the events concerning the cap tend to be broader in nature, I exclude these events as a robustness check. As shown in Figure C.1, the results turn out to be robust. I have also tried to exclude the events about international credits, which affect the supply of allowances only indirectly, by changing the number of credits from international projects that can be exchanged for allowances. From Figure C.2, we can see that the results turn out to be very similar. By going through all events in detail, I could also identify some events that are potentially confounded, either because some other event happened on the same day (more on this below) or because they could potentially also contain some information about demand in the carbon market. Reassuringly, however, excluding these events does not change the results materially (see Figure C.3).

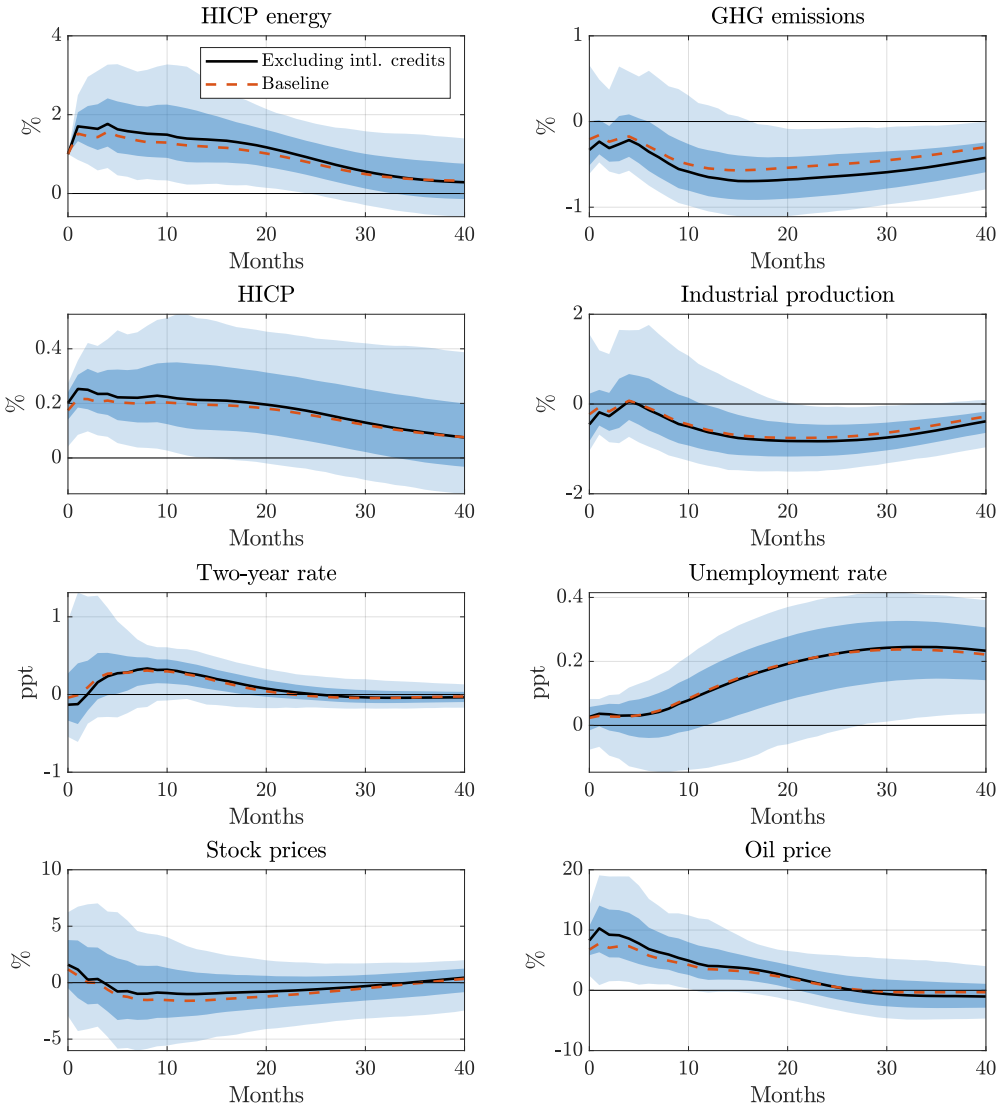
The results are also not driven by events in a given period. Excluding events in phase 1 (2005-2007) or events that occurred during the and European sovereign debt crisis (2009-2012) produces comparable results, see Figures C.4-C.5.



First stage regression: F-statistic: 18.97, R^2: 3.09%

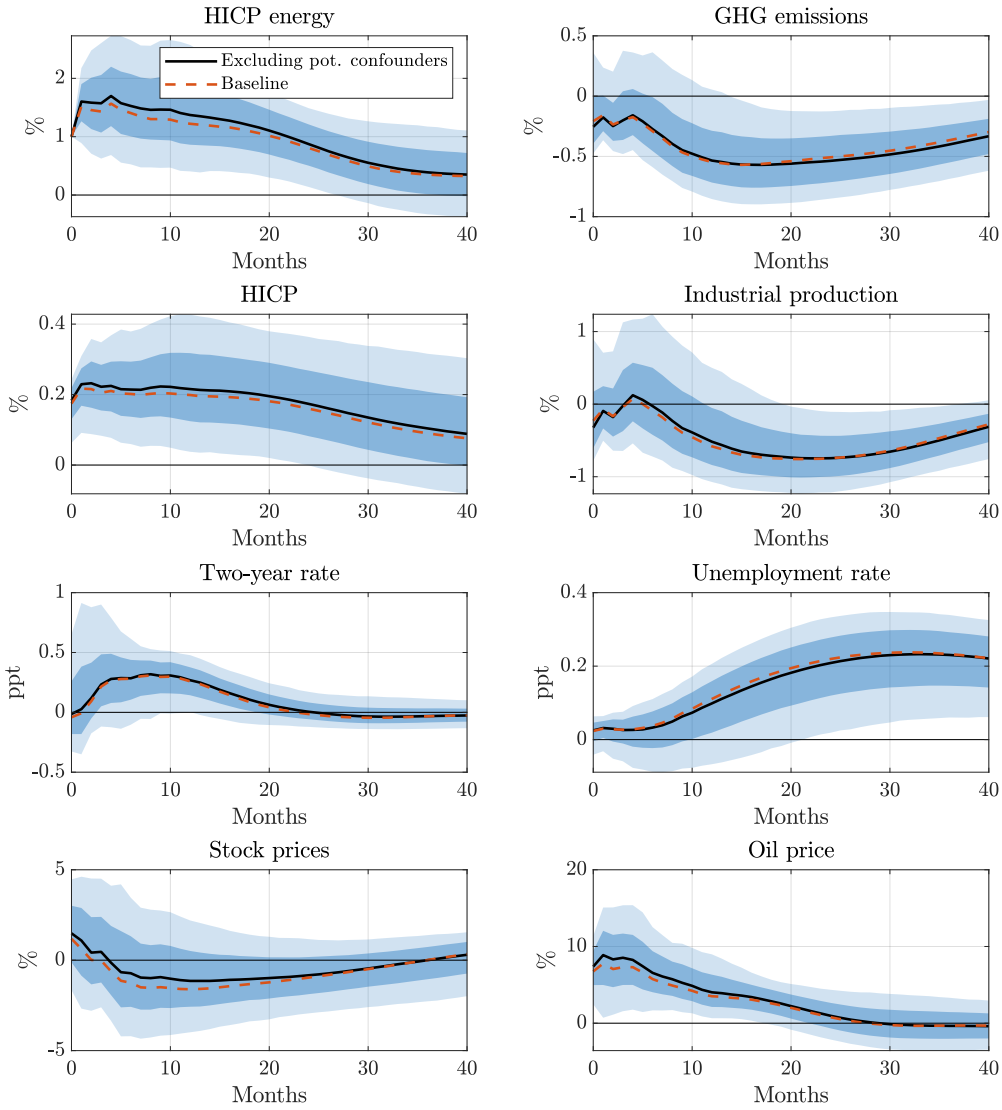
Figure C.1: Excluding Events Regarding Cap

Notes: Impulse responses to a carbon policy shock, normalized to increase the HICP energy by 1 percent on impact. The solid line is the point estimate and the dark and light shaded areas are 68 and 90 percent confidence bands, respectively.



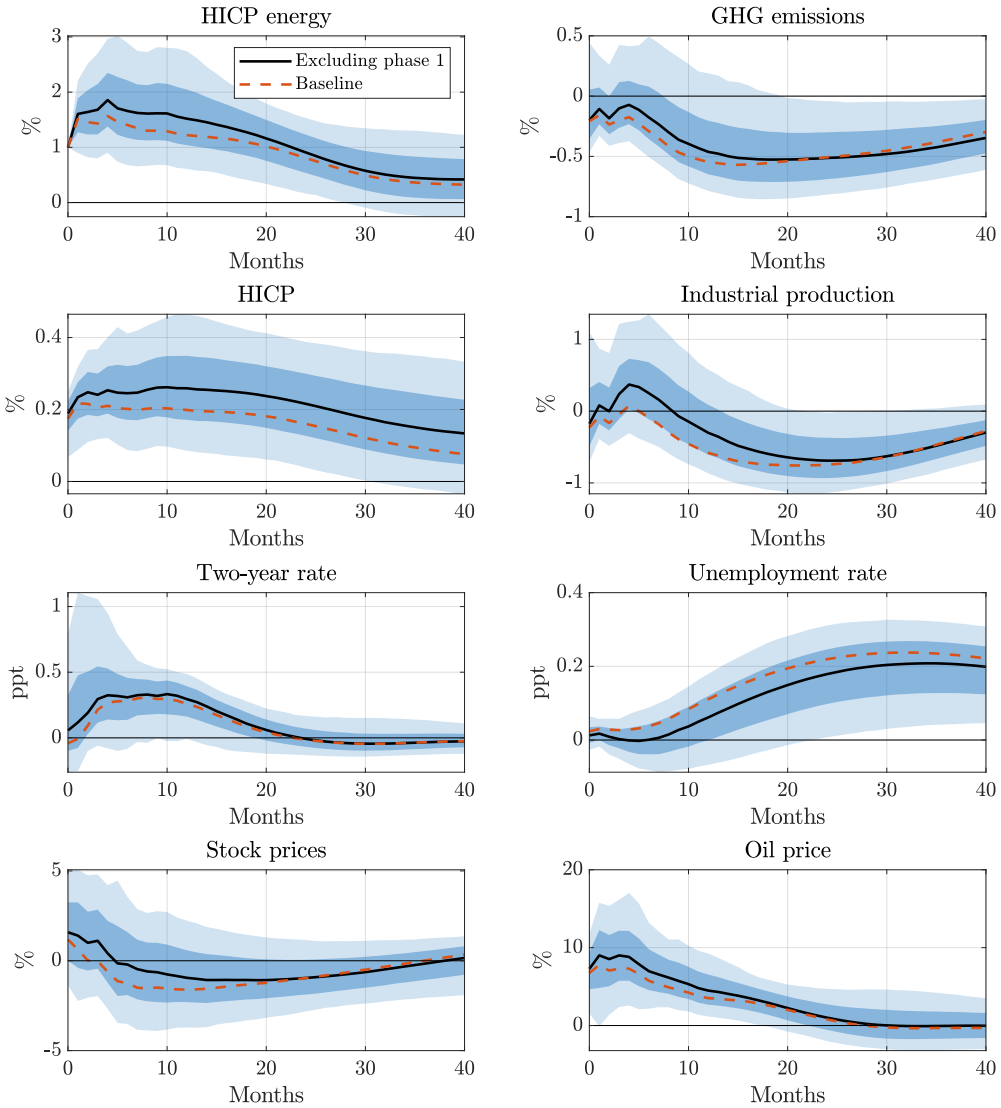
First stage regression: F-statistic: 11.99, R^2: 1.79%

Figure C.2: Excluding Events Regarding International Credits



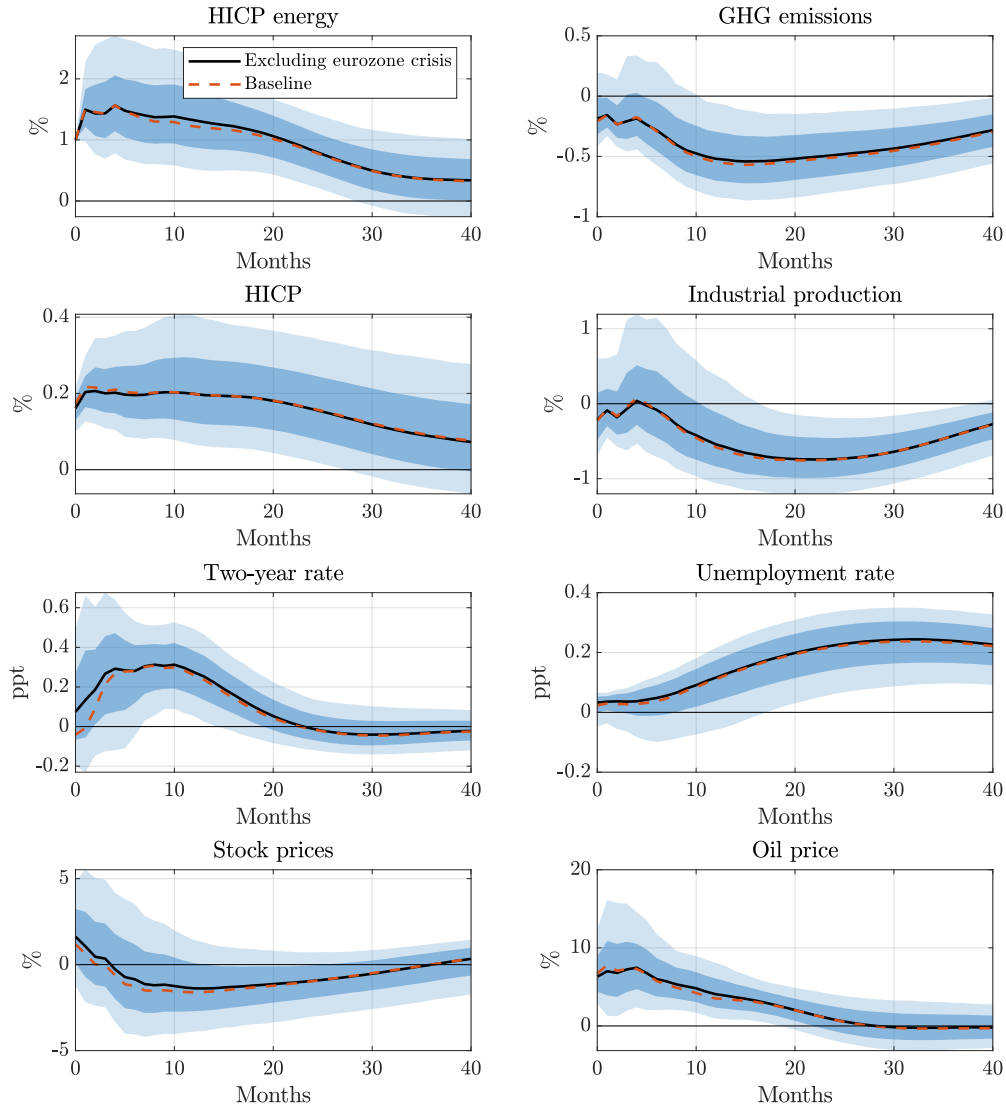
First stage regression: F-statistic: 17.30, R^2: 2.74%

Figure C.3: Excluding Potentially Confounded Events



First stage regression: F-statistic: 16.92, R^2: 2.71%

Figure C.4: Excluding Phase One Events



First stage regression: F-statistic: 21.81, R^2: 3.20%

Figure C.5: Excluding Events During European Sovereign Debt Crisis

Alternative instrument. As discussed in the paper, I measure the carbon policy surprises as the change in the EUA futures price on the day of the regulatory event relative to the prevailing wholesale electricity price on the day before the event. A key advantage of this approach is that it directly gives a notion of how economically relevant a carbon policy surprise is. In particular, it gives less weight to large percentage changes in carbon prices that occurred in an environment where carbon prices were very low. An alternative approach is to simply measure the surprise as the percentage change in the carbon price on event days. To fix ideas, the carbon policy surprise is in this case computed as follows:

$$CPSurprise_{t,d} = \log(F_{t,d}^{carbon}) - \log(F_{t,d-1}^{carbon})$$

where d and t indicate the day and the month of the event, respectively and $F_{t,d}$ is the settlement price of the EUA futures contract. This measure has the advantage that it is less focused on the electricity market but on carbon markets more broadly. However, because this approach generates one relatively large surprise in November 2007 when carbon prices were approaching zero, I exclude this event from the analysis.[4]

Figure C.6: Alternative Carbon Policy Surprise Series

Notes: The figure shows the carbon policy surprise series, measured as the percentage change in carbon prices around event days, compared to the baseline carbon policy surprise series, which is expressed relative to the prevailing wholesale electricity price before the event.

Figure C.6 shows the carbon policy surprise series, measured as the percentage change in carbon prices, relative to the baseline surprise series. We can see that the series are fairly similar, particularly during phase two and the beginning of the third phase. Overall, the two series are highly correlated, with a correlation coefficient of about 0.7.

Reassuringly, using the alternative instrument produces consistent results. Figure C.7 presents the impulse responses to a carbon policy shock using the alternative instrument, together with the baseline responses. We can see that the responses are very similar, both qualitatively and quantitatively. This illustrates the benefits of using the surprise series as an instrument as opposed to a direct shock measure.

[4]In a previous version of the paper, I used this measure of the carbon policy surprise series as the baseline. Interestingly, this produces very similar results, even when including the November 2007 event.

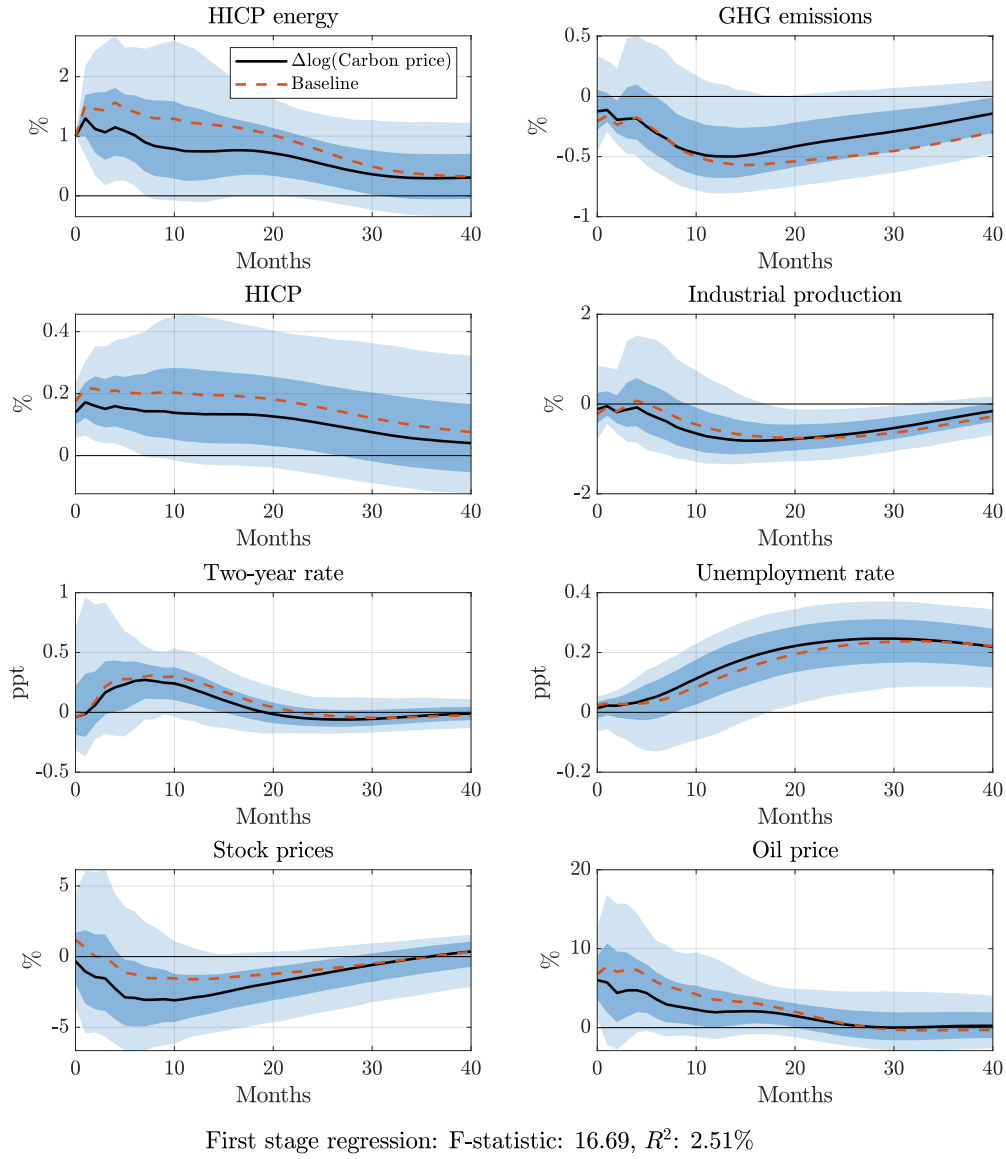


Figure C.7: Instrument Based on Percentage Change in Carbon Price

Futures contracts. EUA futures are traded at different maturities. I focus on the contracts traded on a quarterly cycle. As a baseline, I use the front contract, which is the contract with the closest expiry date and is the most liquid. Figure C.8 presents the results based on other contracts. Overall, the responses turn out to be robust to using contracts with longer maturities. This supports the notion that the results are not severely affected by changes in risk premia.

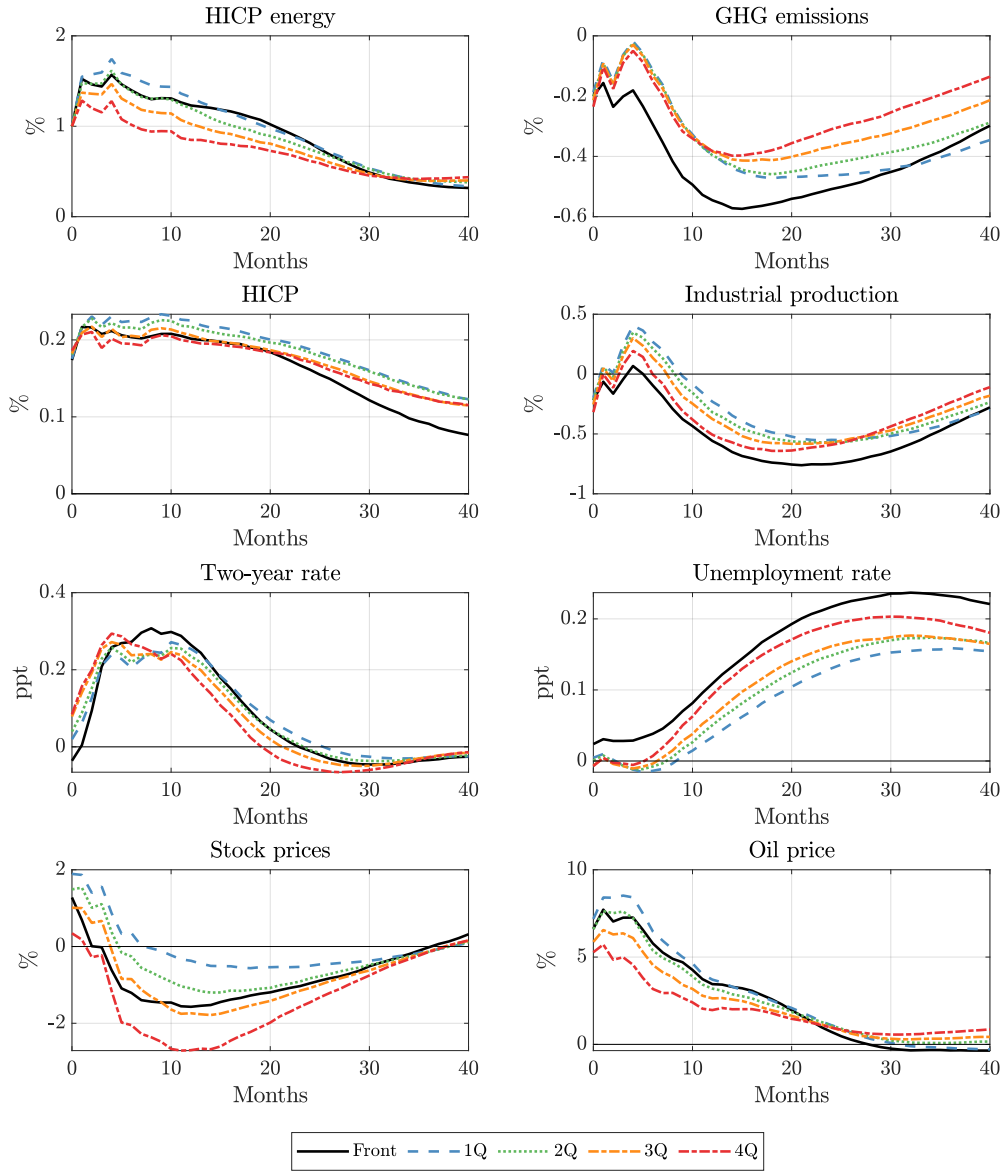


Figure C.8: Using Different Futures Contracts

C.2. Confounding news

Another important choice in high-frequency identification concerns the size of the event window. As discussed in Section 2.2, there is a trade-off between capturing the entire response to the policy news and background noise, i.e. the threat of other news confounding the response. Common window choices range from 30-minutes to multiple days. Unfortunately, the exact release times are unavailable for the majority of the policy events considered, making it infeasible to use an intraday window. Therefore, I use a daily window to compute the policy surprises.

To mitigate concerns about other news confounding the carbon policy surprise series, I employ an alternative identification strategy exploiting the heteroskedasticity in the data (Rigobon, 2003; Nakamura and Steinsson, 2018). The idea is to clean out the background noise in the surprise series by comparing movements in carbon prices during policy event windows to other equally long and otherwise similar event windows that do not contain a regulatory update event. In particular, I use the changes in carbon futures prices on the same weekday and week in the months prior a given regulatory event.

The identification strategy works as follows. Suppose that movements in the EUA futures z_t we observe in the data are governed by both carbon policy and other shocks:

$$z_t = \varepsilon_{1,t} + \sum_{j \neq 1} \varepsilon_{j,t} + v_t,$$

where $\varepsilon_{j,t}$ are other shocks affecting carbon futures and $v_t \sim iidN(0, \sigma_v^2)$ captures measurement error such as microstructure noise. Because z_t is also affected by other shocks, it is no longer a valid external instrument. However, we can still identify the structural impact vector by exploiting the heteroskedasticity in the data.

The identifying assumption is that the variance of carbon policy shocks increases at the time of regulatory update events while the variance of all other shocks is unchanged. Define $R1$ as a sample of regulatory events in the EU ETS and $R2$ as a sample of trading days that do not contain an regulatory event but are comparable on other dimensions. $R1$ can be thought of as the treatment and $R2$ as the control sample. The identifying assumptions can then be written as follows

$$\begin{aligned} \sigma^2_{\varepsilon_1,R1} &> \sigma^2_{\varepsilon_1,R2} \\ \sigma^2_{\varepsilon_j,R1} &= \sigma^2_{\varepsilon_j,R2}, \quad \text{for } j = 2, \ldots, n. \\ \sigma^2_{v,R1} &= \sigma^2_{v,R2}. \end{aligned} \tag{3}$$

Under these assumptions, the structural impact vector is given by

$$\mathbf{s}_1 = \frac{\mathbb{E}_{R1}[z_t \mathbf{u}_t] - \mathbb{E}_{R2}[z_t \mathbf{u}_t]}{\mathbb{E}_{R1}[z_t^2] - \mathbb{E}_{R2}[z_t^2]}. \tag{4}$$

As shown by Rigobon and Sack (2004), we can also obtain this estimator through an IV approach, using $\tilde{\mathbf{z}} = (\mathbf{z}'_{R1}, \ -\mathbf{z}'_{R2})'$ as an instrument in a regression of the reduced-form innovations on $\mathbf{z} = (\mathbf{z}'_{R1}, \ \mathbf{z}'_{R2})'$.

The assumption that the variance of the surprise series is much larger on event days than on a sample of controls days is indeed supported by the data. Figure C.9 shows the carbon policy surprise series together with the control series. We can see that the policy surprise series is much more volatile than the control series, and a Brown–Forsythe test for the equality of group variances confirms that this difference is also statistically significant.

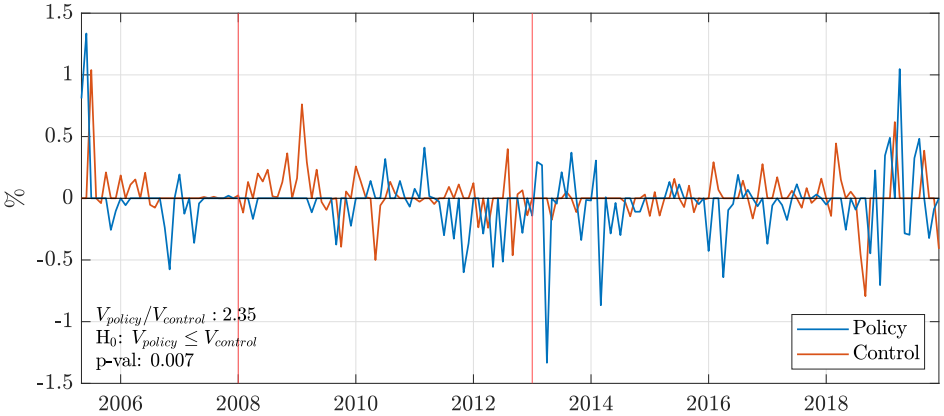


Figure C.9: The Carbon Policy and the Control Series

Notes: This figure shows the carbon policy surprise series together with the surprise series constructed on a selection of control days that do not contain a regulatory announcement but are otherwise similar.

Figure C.10 shows the impulse responses estimated from this alternative approach. The results turn out to be consistent with the baseline results from the external instrument approach, even though the responses are a bit less precisely estimated. These results suggest that the bias induced by background noise is likely negligible in the present application. However, part of the statistical strength under the external/internal instrument approach appears to come from the stronger identifying assumptions.

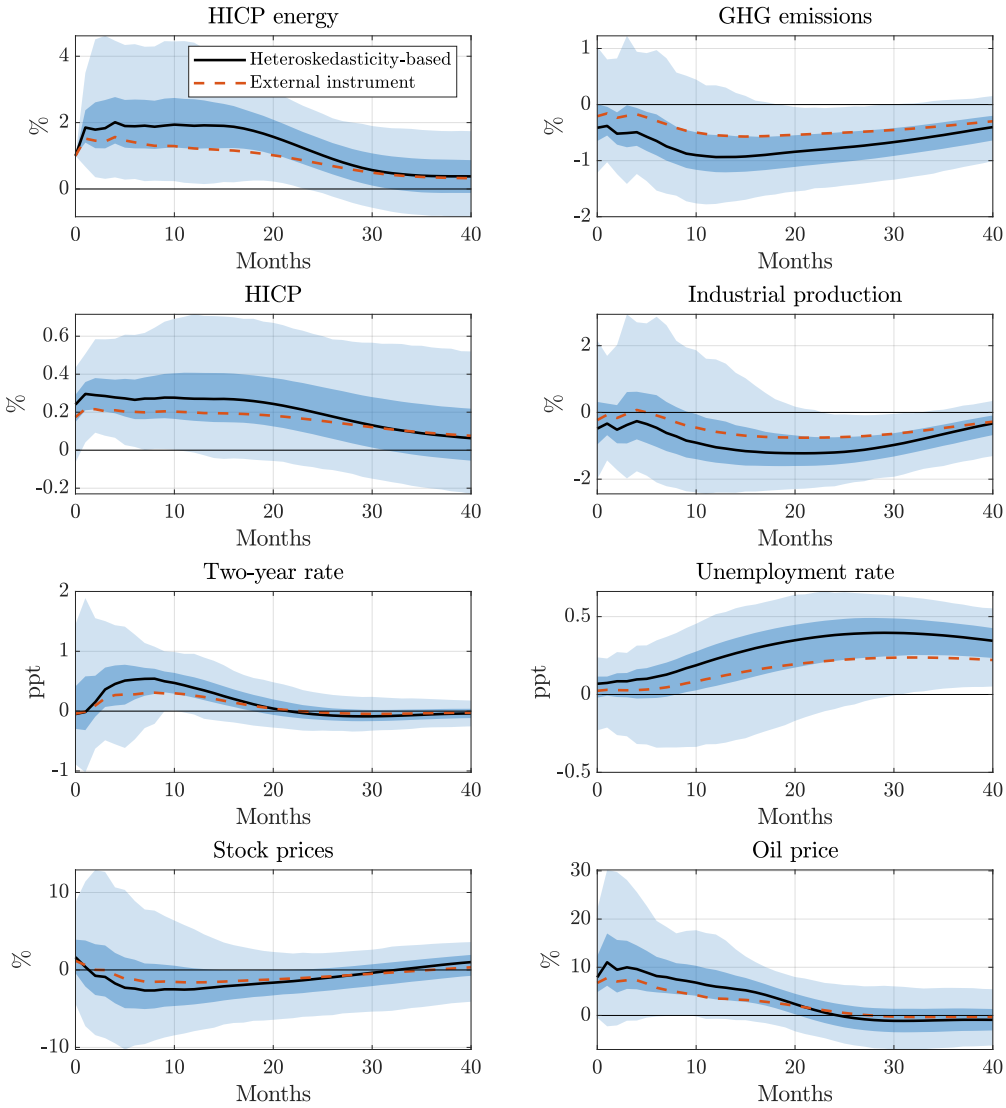


Figure C.10: Heteroskedasticity-based Identification

Interestingly, the heteroskedasticity turns out to be even more stark when using the percentage change in the carbon price as the relevant instrument. As we can see from Figure C.11, in this case, the variance of the surprise series is close to 7 times larger than the variance of the control series. As shown in Figure C.12, this helps to increase the precision of the estimated responses. Reassuringly, the point estimates are again very similar to the baseline external instrument results.

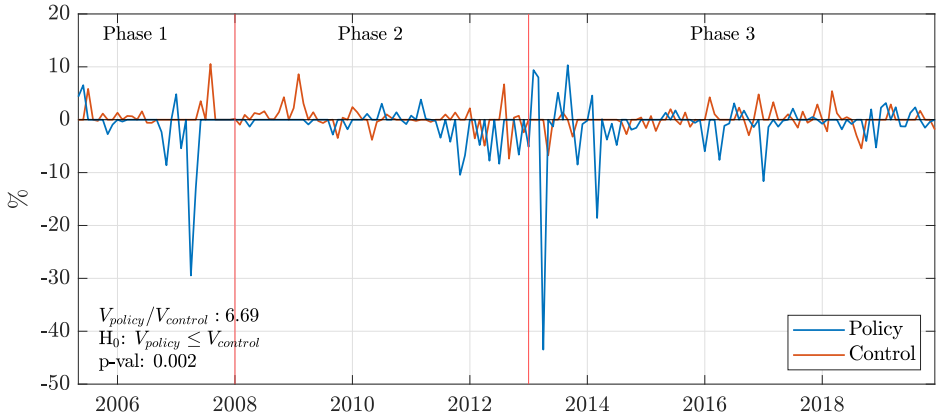


Figure C.11: The Alternative Carbon Policy and the Control Series

Notes: This figure shows the alternative carbon policy surprise series based on the percentage change in carbon prices together with the surprise series constructed on a selection of control days.

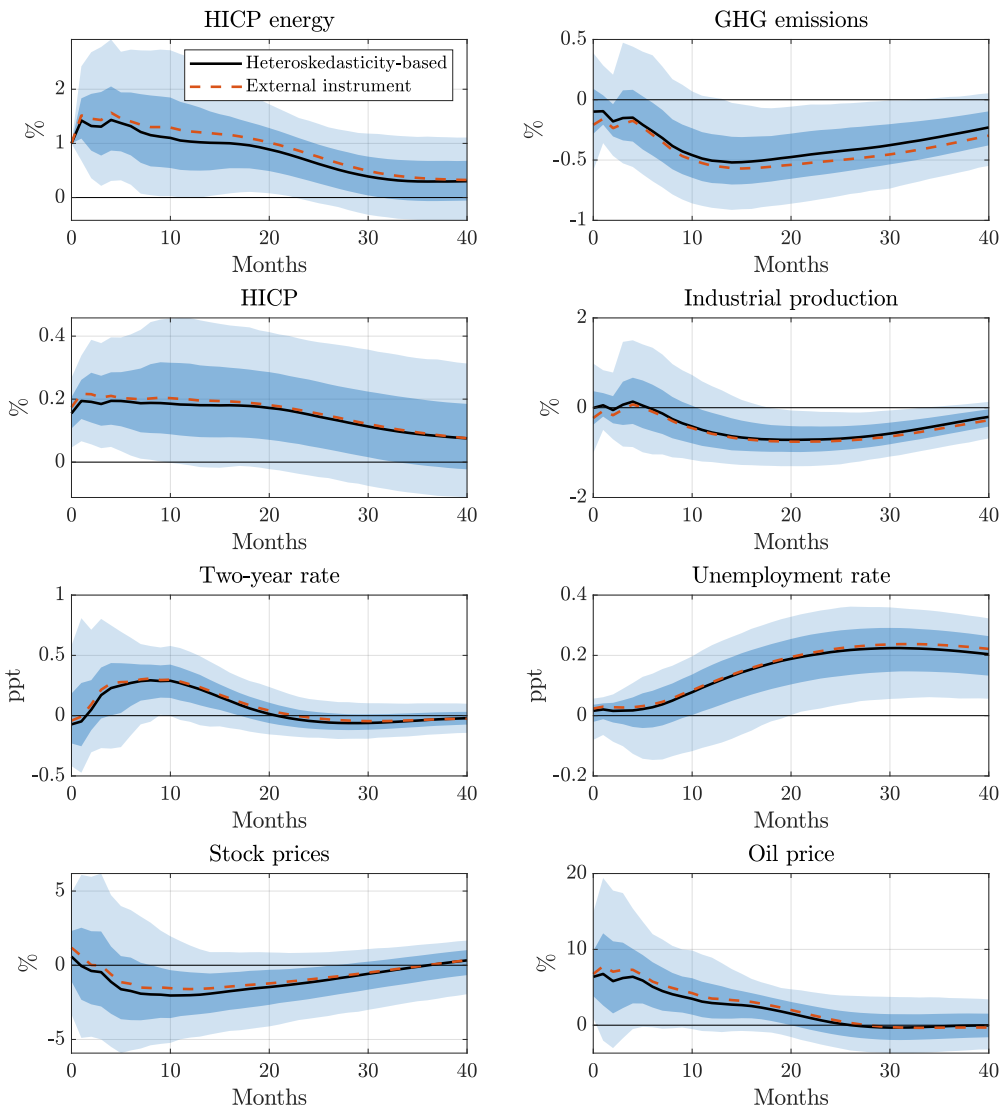


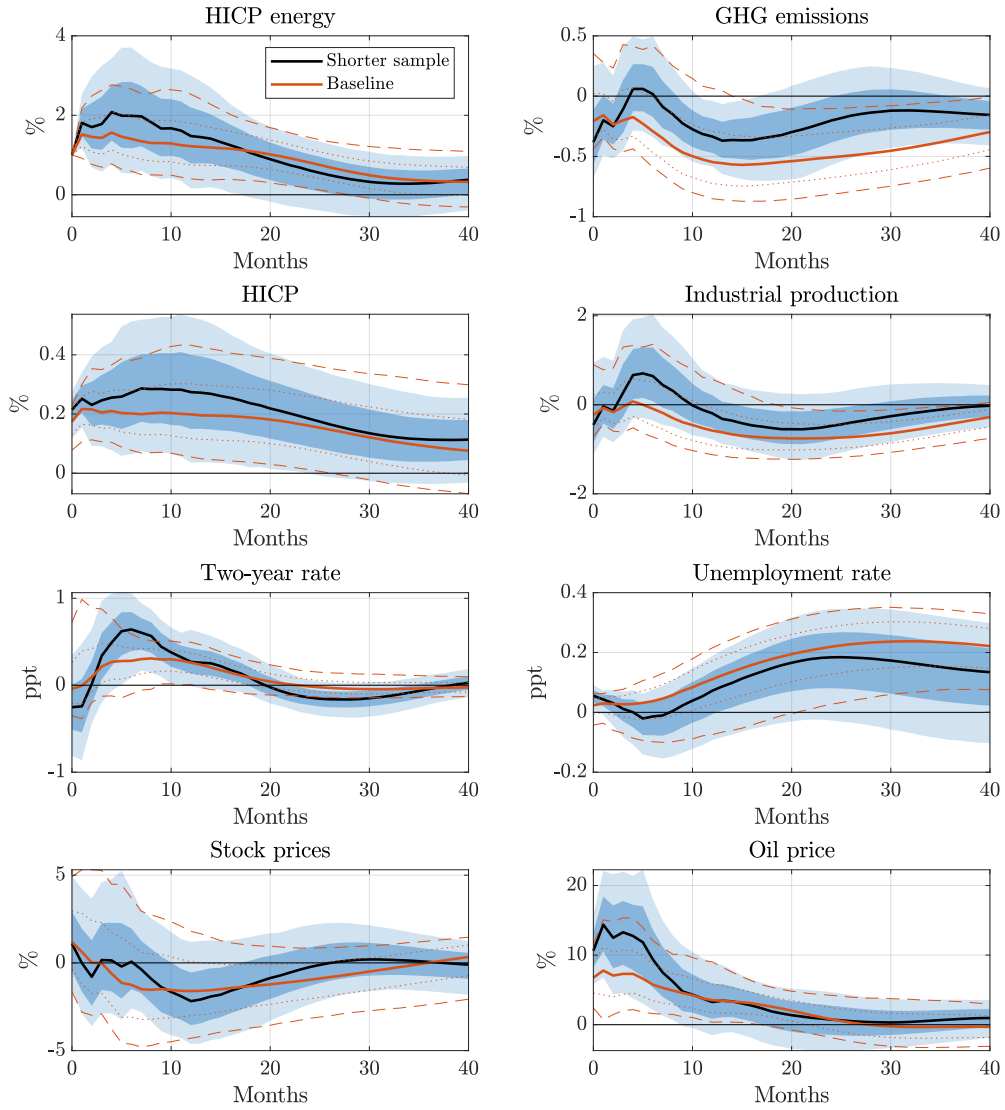
Figure C.12: Heteroskedasticity-based Identification Using Alternative Surprise Series

C.3. Sample and specification choices

An important robustness check concerns the estimation sample. Recall, the baseline sample goes back to 1999, which is longer than the instrument sample which only starts in 2005. The main motivation for using the longer sample is to increase the precision of the estimates. As a robustness check, I restrict the overall sample to the 2005-2019 period. The responses are shown in Figure C.13. Overall, the results are very similar to the ones using the longer sample. However, some responses turn out to be a bit less stable, which could point to difficulties in estimating the model dynamics on the relatively short sample.

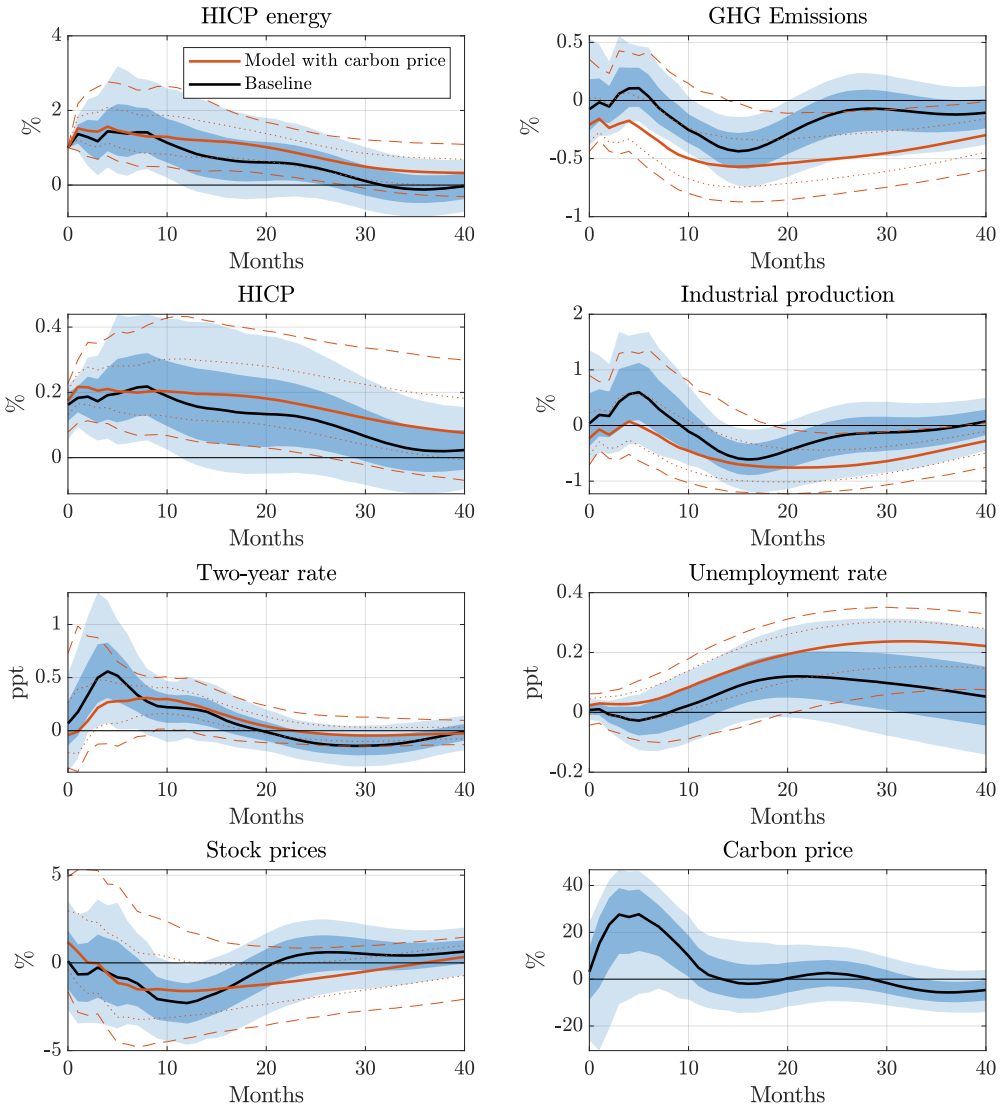
One advantage of the shorter sample is that it is possible to include the carbon price. Figure C.14 shows the response from a model that includes the carbon price in lieu of the oil price. We can see that the shock leads to a significant increase in the carbon price, in line with the interpretation of a shock tightening the carbon pricing regime. Interestingly, however, the carbon price response turns out to be less persistent than the energy price response. We can also back out the elasticity of energy to carbon prices, which turns out to be around 4 percent at the peak. This lies in the ballpark of the average emissions cost share of EU power producers.

I also perform a number of other sensitivity checks on the specification of the model. The baseline VAR includes 8 variables, which is relatively large, especially given the short sample. As a robustness test, I use a 6-variable model, excluding stock prices and the oil price. As can be seen from Figure C.15, the results from this smaller model turn out to be very similar to the larger baseline model. The results also turn out to be robust to the lag order (Figure C.16 shows the responses using 3, 9 or 12 lags) and the choice of deterministics (Figure C.17 includes a linear trend). Only the responses in the model with 3 lags are somewhat different for some variables. This illustrates the importance of controlling for sufficient lags to adequately capture the dynamic relationships in the data. The models with more generously parameterized lag orders produce very similar results to the baseline model with 6 lags.



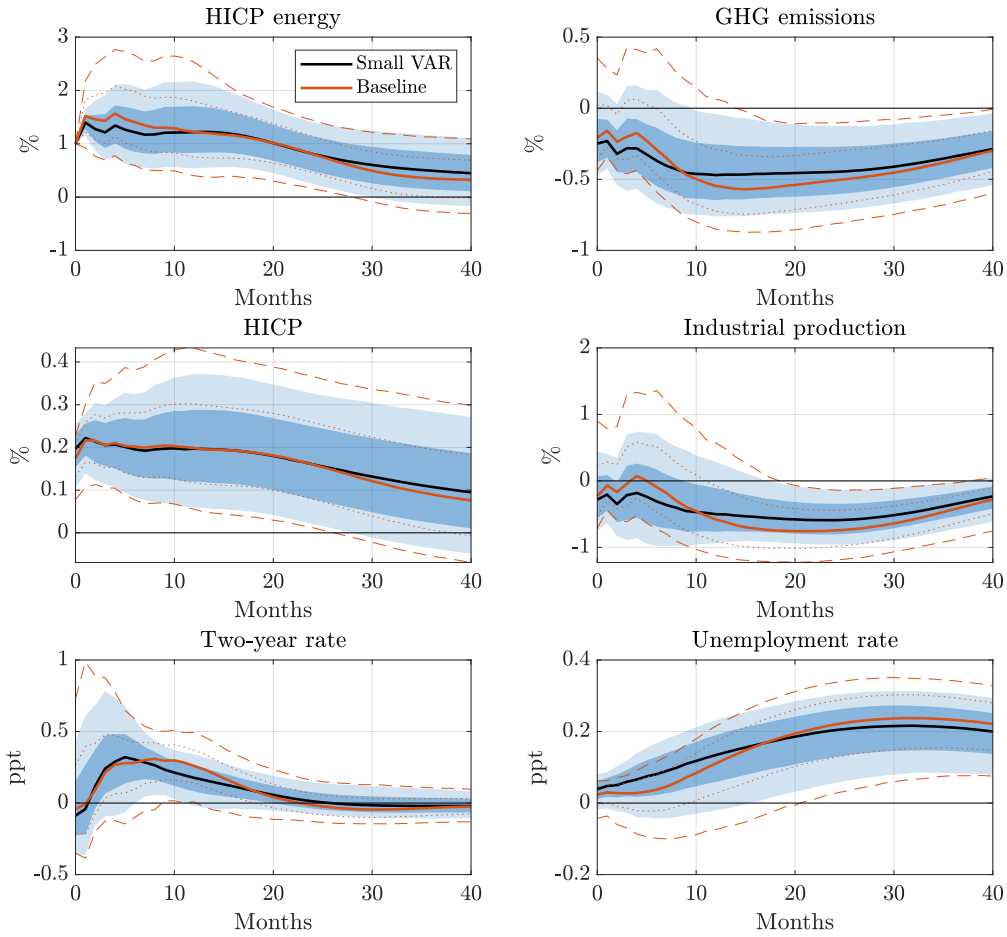
First stage regression: F-statistic: 6.44, R^2: 2.49%

Figure C.13: Results Using 2005-2019 Sample



First stage regression: F-statistic: 9.54, R^2: 4.06%

Figure C.14: Model Including Carbon Spot Price



First stage regression: F-statistic: 6.72, R^2: 1.82%

Figure C.15: Responses from Smaller VAR

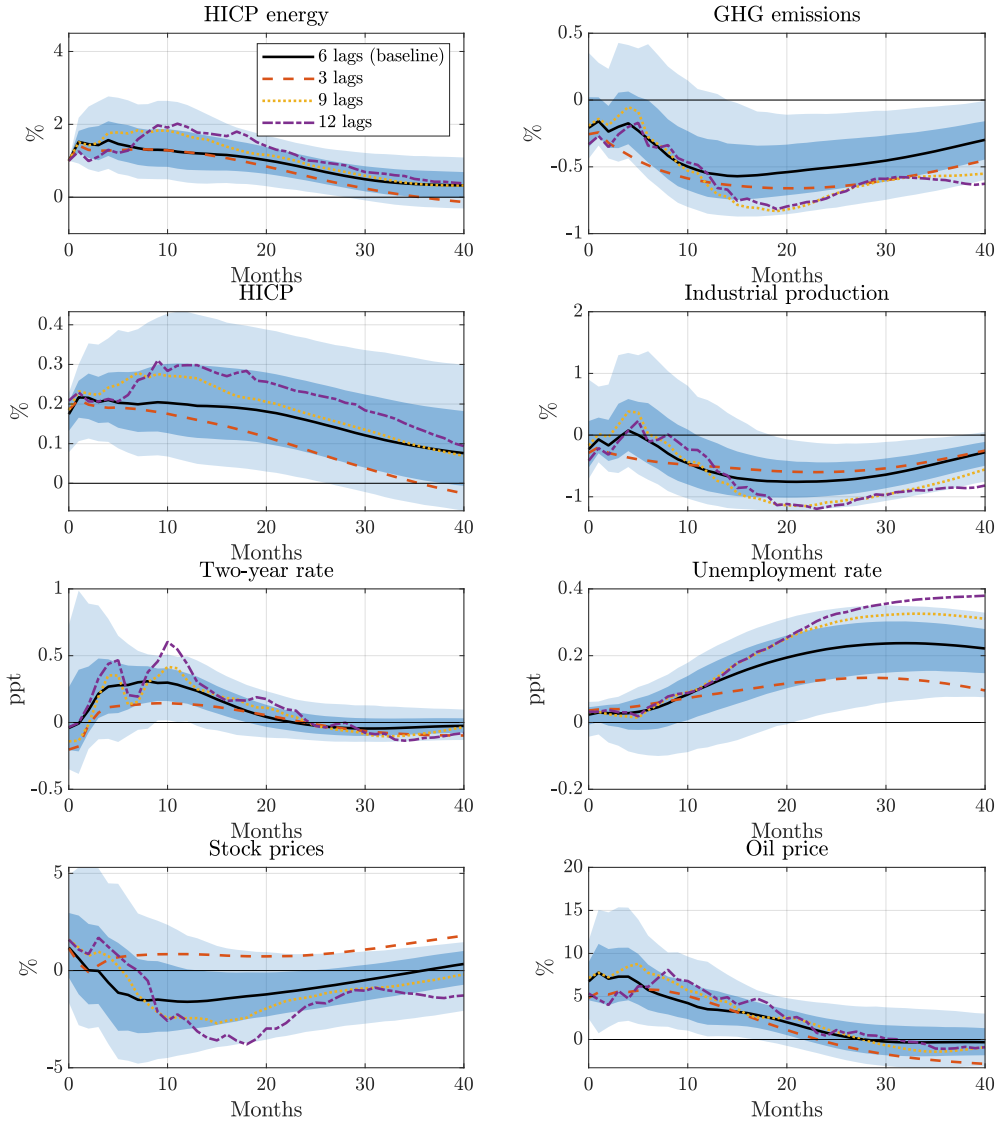
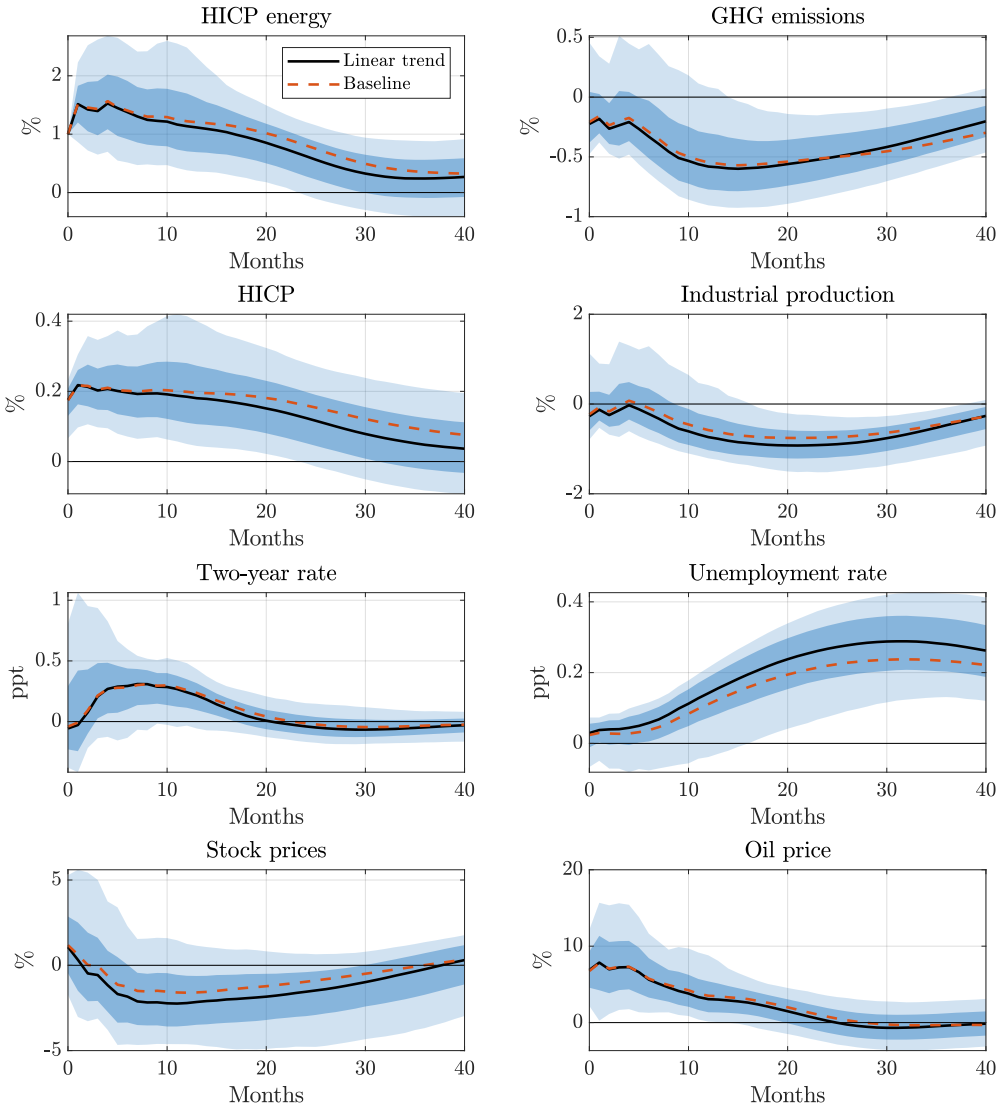


Figure C.16: VARs with Different Lag Orders



First stage regression: F-statistic: 14.60, R^2: 2.68%

Figure C.17: VAR Including Linear Trend

D. A heterogeneous-agent climate-economy model: Derivations

In this appendix, I provide the derivations for the heterogeneous-agent climate-economy model. As discussed in the main text, the aim is to obtain a framework that can account for the empirical findings – both at the aggregate level and along the cross section – and can be used for policy experiments. The model combines a climate-economy structure in the spirit of Golosov et al. (2014) with nominal rigidities, household heterogeneity and risk. The model consists of four building blocks: households, firms, a government and a climate block. The household block consists of two types of households: Households in the *hand-to-mouth* (H) and *savers* (S) state, that differ in their MPCs, income incidence and energy shares. We incorporate idiosyncratic risk by assuming that households switch exogenously between types. The firm block is further divided into consumption good and energy producers. In this appendix, we go over each model block in detail.

D.1. Households

The household sector consists of a continuum of infinitely lived households, indexed by $i \in [0, 1]$. Households are assumed to have identical preferences with felicity function $U(x, h)$, deriving utility from consumption x and disutility from labor h. We assume that the felicity function is of the constant elasticity class and separable in consumption and labor:

$$U(x_{i,t}, h_{i,t}) = \frac{x_{i,t}^{1-\sigma} - 1}{1-\sigma} - \psi_i \frac{h_{i,t}^{1+\theta}}{1+\theta},$$

where $1/\sigma$ is the intertemporal elasticity of substitution and $1/\theta$ is the labor supply elasticity.

Households have access to three assets: a risk-free bond, shares in imperfectly competitive firms, and physical capital. They participate infrequently in financial markets. When they do, they can freely adjust their portfolio and receive dividends from dividends and capital income. We call this the savers' state (S). When agents do not participate in financial markets, they can use only bonds to smooth consumption. We call this the hand-to-mouth state (H). We denote by s the probability to keep participating capital markets in period $t+1$, conditional upon participating at t, i.e. $s = p(s_{t+1}^j = S | s_t^j = S)$, where s_t^j is the current state of household j. Similarly, we call h the probability to keep being excluded from

financial markets, i.e. $h = p(s^j_{t+1} = H | s^j_t = H)$. Hence, the probability to become a financial market participant is $(1-h)$. The share of hand-to-mouth households thus evolves as $\lambda_{t+1} = h\lambda_t + (1-s)(1-\lambda_t)$. We focus on the stationary equilibrium with $\lambda = (1-s)/(2-s-h)$, which is the *unconditional* probability of being hand-to-mouth.

The requirement $s \geq 1-h$ ensures stationary and has a straightforward interpretation: the probability to remain in state S is larger than the probability to move to state S (the conditional probability is larger than the unconditional one). In the limit case of $s = 1-h = 1-\lambda$, idiosyncratic shocks are iid: being S or H tomorrow is independent on whether one is S or H today. At the other extreme stands TANK: idiosyncratic shocks are permanent ($s = h = 1$) and λ stays at its initial value (a free parameter).

We make two key assumptions to obtain a tractable representation. First, there is perfect insurance among the households in a particular state but not between households in different states. Accordingly, we can think of households as living on two different islands and that within each island all resources are pooled. Households on the same island will thus make the same consumption and saving choices. Second, however, we assume that stocks and capital are *illiquid*. When savers can no longer participate in financial markets, they cannot take their stock and capital holdings with them. Only bonds are liquid and can be transferred when switching between islands.

The timing is as follows. At the beginning of every period, resources within types are pooled. The aggregate shocks are revealed and households make their consumption and saving choices. Next, households learn their state in the next period and have to move to the corresponding island accordingly, taking an (equally-split) fraction of the bonds on the current island with them.

The flows across islands are as follows. The total measure of households leaving the H island each period is the number of households who participate next period: $\lambda(1-h)$. The measure of households staying on the island is thus λh. In addition, a measure $(1-\lambda)(1-s)$ leaves the S island for the H island at the end of each period. Recall that our assumptions regarding insurance imply symmetric consumption/saving choices for all households in a given island. Denote by $b_{S,t+1}$ the per-capita beginning-of-period $t+1$ bonds of S (after the consumption-saving choice, and *also after* changing state and pooling). The end-of-period t per capita real values (after the consumption/saving choice but *before* agents move across islands) are $z_{S,t+1}$. Likewise, $b_{H,t+1}$ is the per capita beginning-of-period $t+1$ bonds in the H island (where the only asset is bonds). The end-of-period t values (before agents move across islands) are $z_{H,t+1}$. We have the following

relations:

$$\mathbf{b}_{S,t+1} = (1-\lambda)b_{S,t+1} = (1-\lambda)sz_{S,t+1} + \lambda(1-h)z_{H,t+1}$$
$$\mathbf{b}_{H,t+1} = \lambda b_{H,t+1} = (1-\lambda)(1-s)z_{S,t+1} + \lambda h z_{H,t+1},$$

where $\mathbf{b}_{i,t+1}$, $i \in \{S, H\}$ denote the bond holdings of the entire island. As stocks and capital do not leave the S island, we do not have to keep track of them.

Capital accumulation is simply characterized by:

$$k_{t+1} = i_t - \frac{\varphi_k}{2}\left(\frac{i_t}{k_t} - \delta\right)^2 k_t + (1-\delta)k_t,$$

where δ is the depreciation rate and φ_k is a parameter that governs the costs of adjusting the capital stock.

The program of savers reads

$$V^S(\mathbf{b}_{S,t}, \omega_t, k_t) = \max_{x_{S,t}, z_{S,t+1}, \omega_{t+1}, k_{t+1}, i_t, h_{S,t}} \frac{(x_{S,t})^{1-\sigma}}{1-\sigma} - \psi_S \frac{h_{S,t}^{1+\theta}}{1+\theta} + \beta E_t V^S(\mathbf{b}_{S,t+1}, \omega_{t+1}, k_{t+1}) + \beta \frac{\lambda}{1-\lambda} E_t V^H(\mathbf{b}_{H,t+1})$$

subject to

$$p_{S,t}x_{S,t} + z_{S,t+1} + \nu_t \frac{\omega_{t+1}}{1-\lambda} + \frac{i_t}{1-\lambda} = w_t h_{S,t} + \frac{R_{t-1}^b}{\Pi_t}\frac{\mathbf{b}_{S,t}}{1-\lambda} + \left(\nu_t + (1-\tau^d)d_t\right)\frac{\omega_t}{1-\lambda} + (1-\tau^k)r_t\frac{k_t}{1-\lambda} + \omega_{S,t}$$
$$k_{t+1} = i_t - \frac{\varphi_k}{2}\left(\frac{i_t}{k_t} - \delta\right)^2 k_t + (1-\delta)k_t$$
$$\mathbf{b}_{S,t+1} = (1-\lambda)sz_{S,t+1} + \lambda(1-h)z_{H,t+1}$$
$$\mathbf{b}_{H,t+1} = (1-\lambda)(1-s)z_{S,t+1} + \lambda h z_{H,t+1}$$
$$z_{S,t+1} \geq 0.$$

The household internalizes how aggregate bond holdings evolve according to households switching between types. Furthermore, the bond holdings a household takes from an island cannot be negative, i.e. borrowing is not possible.

The first-order conditions read

$$
\begin{aligned}
\frac{x_{S,t}^{-\sigma}}{p_{S,t}} &= \lambda_{S,t} \\
\lambda_{S,t} &= \beta(1-\lambda)sE_t[V_b^S(\mathbf{b}_{S,t+1},\omega_{t+1},k_{t+1})] + \beta\lambda(1-s)E_t[V_b^H(\mathbf{b}_{H,t+1})] + \xi_{S,t} \\
\frac{\lambda_{S,t}\nu_t}{1-\lambda} &= \beta E_t[V_\omega^S(\mathbf{b}_{S,t+1},\omega_{t+1},k_{t+1})] \\
\zeta_t &= \beta E_t[V_k^S(\mathbf{b}_{S,t+1},\omega_{t+1},k_{t+1})] \\
\frac{\lambda_{S,t}}{1-\lambda} &= \zeta_t\left(1-\varphi_k\left(\frac{i_t}{k_t}-\delta\right)\right) \\
\lambda_{S,t}w_t &= \psi_S h_{S,t}^\theta
\end{aligned}
$$

together with the complementary slackness condition:

$$z_{S,t+1}\xi_{S,t} = 0,$$

with $\xi_{S,t} \geq 0$. $\lambda_{S,t}$, ζ_t and $\xi_{S,t}$ are Lagrange multipliers associated with the budget constraint, capital accumulation, and the inequality constraint, respectively.

From the Envelope theorem, we have

$$
\begin{aligned}
V_b^S(\mathbf{b}_{S,t},\omega_t,k_t) &= \frac{\lambda_{S,t}}{1-\lambda}\frac{R_{t-1}^b}{\Pi_t} \\
V_\omega^S(\mathbf{b}_{S,t},\omega_t,k_t) &= \frac{\lambda_{S,t}}{1-\lambda}\left(\nu_t + (1-\tau^d)d_t\right) \\
V_k^S(\mathbf{b}_{S,t},\omega_t,k_t) &= \frac{\lambda_{S,t}}{1-\lambda}(1-\tau^k)r_t + \zeta_t\left(1-\delta-\frac{\varphi_k}{2}\left(\frac{i_t}{k_t}-\delta\right)^2 + \varphi_k\left(\frac{i_t}{k_t}-\delta\right)\frac{i_t}{k_t}\right).
\end{aligned}
$$

Using this in the FOCs gives

$$
\begin{aligned}
\frac{x_{S,t}^{-\sigma}}{p_{S,t}} &= \lambda_{S,t} \\
\lambda_{S,t} &= \beta s E_t\left[\lambda_{S,t+1}\frac{R_t^b}{\Pi_{t+1}}\right] + \beta\lambda(1-s)E_t[V_b^H(\mathbf{b}_{H,t+1})] + \xi_{S,t} \\
\lambda_{S,t} &= \beta E_t\left[\lambda_{S,t+1}\frac{\nu_{t+1}+(1-\tau^d)d_{t+1}}{\nu_t}\right] \\
\zeta_t &= \beta E_t\left[\frac{\lambda_{S,t+1}}{1-\lambda}(1-\tau^k)r_{t+1} + \zeta_{t+1}\left(1-\delta-\frac{\varphi_k}{2}\left(\frac{i_{t+1}}{k_{t+1}}-\delta\right)^2 + \varphi_k\left(\frac{i_{t+1}}{k_{t+1}}-\delta\right)\frac{i_{t+1}}{k_{t+1}}\right)\right] \\
\frac{\lambda_{S,t}}{1-\lambda} &= \zeta_t\left(1-\varphi_k\left(\frac{i_t}{k_t}-\delta\right)\right) \\
\lambda_{S,t}w_t &= \psi_S h_{S,t}^\theta.
\end{aligned}
$$

Tobin's marginal q is defined as $q_t = \frac{\zeta_t}{\lambda_{S,t}/(1-\lambda)}$. Using this, we can rewrite the optimal capital and investment decision as

$$q_t = \beta E_t \left[\frac{\lambda_{S,t+1}}{\lambda_{S,t}} \left((1-\tau^k) r_{t+1} + q_{t+1} \left(1 - \delta - \frac{\varphi_k}{2} \left(\frac{i_{t+1}}{k_{t+1}} - \delta \right)^2 + \varphi_k \left(\frac{i_{t+1}}{k_{t+1}} - \delta \right) \frac{i_{t+1}}{k_{t+1}} \right) \right) \right]$$
$$1 = q_t \left(1 - \varphi_k \left(\frac{i_t}{k_t} - \delta \right) \right).$$

The only thing that remains to be determined is $V_b^H(\mathbf{b}_{H,t+1})$. We can obtain this from the problem of the hand-to-mouth. Their program reads

$$V^H(\mathbf{b}_{H,t}) = \max_{x_{H,t}, z_{H,t+1}, h_{H,t}} \frac{x_{H,t}^{1-\sigma}}{1-\sigma} - \psi_H \frac{h_{H,t}^{1+\theta}}{1+\theta} + \beta E_t V^H(\mathbf{b}_{H,t+1}) + \beta \frac{1-\lambda}{\lambda} E_t V^S(\mathbf{b}_{S,t+1}, \omega_{t+1}, k_{t+1})$$

subject to

$$\begin{aligned}
&p_{S,t} x_{H,t} + z_{H,t+1} = w_t h_{H,t} + \frac{R_{t-1}^b}{\Pi_t} \frac{\mathbf{b}_{H,t}}{\lambda} + \omega_{H,t} \\
&\mathbf{b}_{S,t+1} = (1-\lambda) s z_{S,t+1} + \lambda (1-h) z_{H,t+1} \\
&\mathbf{b}_{H,t+1} = (1-\lambda)(1-s) z_{S,t+1} + \lambda h z_{H,t+1} \\
&z_{H,t+1} \geq 0.
\end{aligned}$$

The first-order conditions read

$$\begin{aligned}
x_{H,t}^{-\sigma} &= \lambda_{H,t} \\
\lambda_{H,t} &= \beta \lambda h E_t [V_b^H(\mathbf{b}_{H,t+1})] + \beta (1-\lambda)(1-h) E_t [V_b^S(\mathbf{b}_{S,t+1}, \omega_{t+1}, k_{t+1})] + \xi_{H,t} \\
\lambda_{H,t} w_t &= \psi_H h_{H,t}^{\theta}
\end{aligned}$$

together with the complementary slackness condition:

$$z_{H,t+1} \xi_{H,t} = 0,$$

with $\xi_{H,t} \geq 0$.

From the Envelope theorem, we have

$$V_b^H(\mathbf{b}_{H,t}) = \frac{\lambda_{H,t}}{\lambda} \frac{R_{t-1}^b}{\Pi_t}.$$

Thus, we can rewrite the Euler equations for bonds accordingly

$$\lambda_{H,t} = \beta E_t \left[\frac{R_t^b}{\Pi_{t+1}} \left(h\lambda_{H,t+1} + (1-h)\lambda_{S,t+1} \right) \right] + \xi_{H,t}$$

and similarly for the savers:

$$\lambda_{S,t} = \beta E_t \left[\frac{R_t^b}{\Pi_{t+1}} \left(s\lambda_{S,t+1} + (1-s)\lambda_{H,t+1} \right) \right] + \xi_{S,t}.$$

Note that the Euler equation for stocks and capital are isomorphic to the conditions in a representative-agent setting. There is no self-insurance motive, for they cannot be carried to the H state.[5]

In contrast, the bond Euler equations are of the same form as in fully-fledged incomplete-markets models of the Bewely-Huggett-Aiyagari type. In particular, the probability $(1-s)$ measures the uninsurable risk to switch to a bad state next period, risk for which only bonds can be used to self-insure, thus generating a demand for bonds for "precautionary" purposes.

Two additional assumptions are required to deliver our simple equilibrium representation. First, we focus on equilibria where (whatever the reason) the constraint of H agents always binds (i.e. $\xi_H > 0$) and their Euler equation is in fact a strict inequality (for instance, because the shock is a "liquidity" or impatience shock making them want to consume more today, or because their average income in that state is lower enough than in the S state, as would be the case if average profits were high enough; or simply because of a technological constraint preventing them from accessing any asset markets) and the constraint of S never binds ($\xi_S = 0$) so that their Euler equation always holds with equality. Second, we focus on the zero-liquidity limit, that is we assume that even though the demand for bonds from S is well-defined (the constraint is not binding), the net supply of bonds is zero, so there are no bonds traded in equilibrium.

Under these assumptions, the H households are indeed hand-to-mouth as their budget constraint reads

$$p_{S,t} x_{H,t} = w_t h_t + \omega_{H,t}. \tag{5}$$

[5] As households pool resources when participating (which would be optimal with t=0 symmetric agents and $t = 0$ trading), they perceive a return conditional on participating next period. This exactly compensates for the probability of not participating next period, thus generating the same Euler equation as with a representative agent.

The intertemporal consumption/saving behavior by savers is characterized by

$$\lambda_{S,t} = \frac{x_{S,t}^{-\sigma}}{p_{S,t}} \tag{6}$$

$$\lambda_{S,t} = \beta E_t \left[\frac{R_t^b}{\Pi_{t+1}} \left(s\lambda_{S,t+1} + (1-s)\lambda_{H,t+1} \right) \right] \tag{7}$$

$$\lambda_{S,t} = \beta E_t \left[\lambda_{S,t+1} \frac{\nu_{t+1} + (1-\tau^d) d_{t+1}}{\nu_t} \right] \tag{8}$$

$$q_t = \beta E_t \left[\frac{\lambda_{S,t+1}}{\lambda_{S,t}} \left((1-\tau^k) r_{t+1} + q_{t+1} \left(1 - \delta - \frac{\varphi_k}{2} \left(\frac{i_{t+1}}{k_{t+1}} - \delta \right)^2 + \varphi_k \left(\frac{i_{t+1}}{k_{t+1}} - \delta \right) \frac{i_{t+1}}{k_{t+1}} \right) \right) \right] \tag{9}$$

$$1 = q_t \left(1 - \varphi_k \left(\frac{i_t}{k_t} - \delta \right) \right) \tag{10}$$

$$p_{S,t} x_{S,t} + i_{S,t} + b_{S,t+1} = w_t h_t + \frac{R_{t-1}^b}{\Pi_t} b_{S,t} + (1-\tau^k) r_t k_{S,t} + \frac{(1-\tau^d) d_t}{1-\lambda} + \omega_{S,t} \tag{11}$$

$$k_{t+1} = i_t - \frac{\varphi_k}{2} \left(\frac{i_t}{k_t} - \delta \right)^2 k_t + (1-\delta) k_t, \tag{12}$$

as market clearing implies that $\omega_t = \omega_{t+1} = 1$.

As to the intratemporal choice between energy and non-energy consumption, recall that the final consumption bundle $x_{S,t}$ is a CES aggregate of consumption and energy goods

$$x_{S,t} = \left(a_{S,c}^{\frac{1}{\epsilon_x}} c_{S,t}^{\frac{\epsilon_x - 1}{\epsilon_x}} + a_{S,e}^{\frac{1}{\epsilon_x}} e_{S,t}^{\frac{\epsilon_x - 1}{\epsilon_x}} \right)^{\frac{\epsilon_x}{\epsilon_x - 1}},$$

where $a_{S,c}$ and $a_{S,e}$ are distribution parameters with $a_{S,c} + a_{S,e} = 1$[6] , and ϵ_x is the

[6]Note that the distribution parameters $a_{S,c}$ and $a_{S,e}$, sometimes also referred to as shares, are in fact not shares but depend on underlying dimensions unless $\epsilon_x = 1$. In other words, these parameters are not deep parameters but depend on a mixture of parameters that depends on the choice of units. To circumvent this issue, we follow the re-parameterization approach proposed by Cantore and Levine (2012). In particular, we calibrate the steady-state energy share and to back out the implied distribution parameters. We have:

$$a_{S,e} = \frac{p_e e_S}{p_S x_S} \left(\frac{p_e}{p_S} \right)^{\epsilon_x - 1} = \omega_{S,e} \left(\frac{p_e}{p_S} \right)^{\epsilon_x - 1},$$

where $\omega_{S,e}$ is the energy expenditure share. From this, we then have $a_{S,c} = 1 - a_{S,e}$. Note that this share is dimensionless. Thus, we can calibrate or estimate it. By using this strategy, we can also perform comparative statics, varying the elasticity ϵ_x.

elasticity of substitution between non-energy and energy goods: $\frac{\partial(c_t/e_{c,t})/(c_t/e_{c,t})}{\partial(p_{e,t}/1)/(p_{e,t}/1)}$.[7] Making the distribution parameters household-specific allows for heterogeneity in the households' energy share.

The demands for the consumption and energy good the are given by

$$c_{S,t} = a_{S,c}\left(\frac{1}{p_{S,t}}\right)^{-\epsilon_x} x_{S,t} \tag{13}$$

$$e_{S,t} = a_{S,e}\left(\frac{p_{e,t}}{p_{S,t}}\right)^{-\epsilon_x} x_{S,t}, \tag{14}$$

respectively. Note that the consumption good is chosen to be the numeraire, i.e. it's price is one in real terms.

The corresponding price index is

$$p_{S,t} = \left(a_{S,c} + a_{S,e}p_{e,t}^{1-\epsilon_x}\right)^{\frac{1}{1-\epsilon_x}}. \tag{15}$$

Similarly, for the hand-to-mouth, we have

$$c_{H,t} = a_{H,c}\left(\frac{1}{p_{S,t}}\right)^{-\epsilon_x} x_{H,t} \tag{16}$$

$$e_{H,t} = a_{H,e}\left(\frac{p_{e,t}}{p_{S,t}}\right)^{-\epsilon_x} x_{H,t} \tag{17}$$

and the price of their bundle is

$$p_{H,t} = \left(a_{H,c} + a_{H,e}p_{e,t}^{1-\epsilon_x}\right)^{\frac{1}{1-\epsilon_x}}. \tag{18}$$

Finally, the optimal labor supply decisions are characterized as

$$\lambda_{S,t}w_t = \psi_S h_{S,t}^{\theta} \tag{19}$$

$$\lambda_{H,t}w_t = \psi_H h_{H,t}^{\theta}. \tag{20}$$

D.2. Firms

The firm block of the model consists of two sectors: energy and non-energy producers. Importantly, non-energy firms also use energy as an intermediate input to produce the non-energy good. Further, we assume that non-energy firms face some restrictions in adjusting their prices while the energy sector does not face

[7] If ϵ_x approaches ∞, the goods are perfect substitutes; if ϵ_x approaches 0, the goods are perfect complements; and if ϵ_x approaches 1, the goods are one-for-one substitutable, which corresponds to the Cobb-Douglas case.

any price rigidity.

Energy producers. The energy firm produces energy using labor only according to the following production function:

$$e_t = a_{e,t} h_{e,t}. \tag{21}$$

We assume that there is only a single source of energy (e.g. coal) that is available in (approx.) infinite supply. Note that we measure energy in terms of carbon content (carbon amount emitted). Energy firms are subject to a carbon tax τ_t.

Their maximization problem reads

$$\begin{aligned} \max_{h_{e,t}} \quad & (1-\tau_t) p_{e,t} e_t - w_t h_{e,t} \\ \text{s.t.} \quad & e_t = a_{e,t} h_{e,t} \end{aligned}$$

The FOC gives the optimal energy supply:

$$\frac{w_t}{(1-\tau_t) p_{e,t}} = \frac{e_t}{h_{e,t}}. \tag{22}$$

Non-energy firms. To simplify matters, we split the non-energy goods sectors into two subsectors: a representative competitive final goods firm which aggregates intermediate goods according to a CES technology and a continuum of intermediate goods producers that produce different varieties using capital, energy and labor as an input. To the extent to which the intermediate goods are imperfect substitutes, there is a downward-sloping demand for each intermediate variety, giving the intermediate producers some pricing power. Importantly, however, intermediate goods producers cannot freely adjust prices. Nominal price rigidities are modeled according to Calvo (1983) mechanism. In each period, a firm faces a constant probability $1-\theta_p$ of being able to reoptimize the nominal wage.

Final goods producer. Final goods firms maximize profits subject to the production function by taking prices as given. Since final goods firms are all identical, we can focus on one representative firm. These firms bundle the differentiated goods into a final good using a CES technology. Taking prices as given, the final goods producer chooses intermediate good quantities $y_t(i)$ to maximize profits:

$$\max_{y_t(i)} P_t y_{d,t} - \int_0^1 P_t(i) y_t(i) di \qquad \text{s.t.} \quad y_{d,t} = \left(\int_0^1 y_t(i)^{\frac{\epsilon_p - 1}{\epsilon_p}} di \right)^{\frac{\epsilon_p}{\epsilon_p - 1}},$$

where $y_{d,t}$ is aggregate demand and $\epsilon_p > 1$ is the elasticity of substitution. When goods are perfectly substitutable $\epsilon_p \to \infty$, we approach the perfect competition benchmark.

From the first order condition, we get the usual demand schedule

$$y_t(i) = \left(\frac{P_t(i)}{P_t}\right)^{-\epsilon_p} y_{d,t}.$$

From the zero profit condition we obtain the aggregate price level $P_t = \left(\int_0^1 P_t(i)^{1-\epsilon_p} dj\right)^{\frac{1}{1-\epsilon_p}}$.

Intermediate goods producers. Intermediate inputs are produced by a continuum of monopolistic firms indexed by $i \in [0,1]$ according to the following CES production technology, using capital $k_t(i)$, energy $e_{y,t}(i)$, and labor $h_{y,t}(i)$ as inputs

$$y_t(i) = e^{-\gamma s_t}\left[(1-\nu)^{1/\epsilon_y}\left(a_t k_t(i)^{\alpha} h_{y,t}(i)^{1-\alpha}\right)^{(\epsilon_y-1)/\epsilon_y} + \nu^{1/\epsilon_y}\left(e_{y,t}(i)\right)^{(\epsilon_y-1)/\epsilon_y}\right]^{\epsilon_y/(\epsilon_y-1)}, \tag{23}$$

where a_t is a technology shifter, and $e^{-\gamma s_t}$ captures climate damages, modeled as a function of the atmospheric carbon concentration s_t. We assume that capital/labor and energy are complements, i.e. $\epsilon_y < 1$.

As intermediate goods producers are monopolists, they maximize profits by taking the demand function of final goods firms into account. We consider now the problem of an intermediate goods firm i. For the sake of simplicity the program is split into two sub-problems: the cost minimization and the price setting problem. To find the real cost function, factor costs are minimized subject to the production function. The program of firm i reads

$$\min_{k_t(i), h_{y,t}(i), e_{y,t}(i)} r_t k_t(i) + w_t h_{y,t}(i) + p_{e,t} e_{y,t}(i)$$

$$\text{s.t.} \quad y_t(i) \leq e^{-\gamma s_t}\left[(1-\nu)^{1/\epsilon_y}\left(a_t k_t(i)^{\alpha} h_{y,t}(i)^{1-\alpha}\right)^{(\epsilon_y-1)/\epsilon_y} + \nu^{1/\epsilon_y}\left(e_{y,t}(i)\right)^{(\epsilon_y-1)/\epsilon_y}\right]^{\epsilon_y/(\epsilon_y-1)}$$

The FOCs read

$$\frac{r_t k_t(i)}{y_t(i)} = \alpha(1-\nu)^{\frac{1}{\epsilon_y}} \lambda_t(i) \left(\frac{e^{-\gamma s_t} a_t k_t(i)^{\alpha} h_{y,t}(i)^{1-\alpha}}{y_t(i)}\right)^{\frac{\epsilon_y-1}{\epsilon_y}}$$

$$\frac{w_t h_{y,t}(i)}{y_t(i)} = (1-\alpha)(1-\nu)^{\frac{1}{\epsilon_y}} \lambda_t(i) \left(\frac{e^{-\gamma s_t} a_t k_t(i)^{\alpha} h_{y,t}(i)^{1-\alpha}}{y_t(i)} \right)^{\frac{\epsilon_y - 1}{\epsilon_y}}$$

$$\frac{p_{e,t} e_{y,t}(i)}{y_t(i)} = \nu^{\frac{1}{\epsilon_y}} \lambda_t(i) \left(\frac{e^{-\gamma s_t} e_{y,t}(i)}{y_t(i)} \right)^{\frac{\epsilon_y - 1}{\epsilon_y}}$$

where $\lambda_t(i)$ is the corresponding Lagrange multiplier. This multiplier has the interpretation as real marginal cost – how much will costs change if you are forced to produce an extra unit of output, i.e. $\lambda_t(i) = mc_t(i)$, and it is equal across firms, i.e. $mc_t(i) = mc_t$. This in turn implies that the output-capital, output-labor, and output-energy ratios are the same across firms.

Now that we have found the real cost function, we can move to the intermediate goods firms' price setting problem. Intermediate goods producers set prices to maximize the expected discounted stream of (real) profits. However, as outlined above, firms are not able to freely adjust price each period. In particular, in each period there is a fixed probability of $1 - \theta_p$ that a firm can adjust its price. Since there is a chance that the firm will get stuck with its price for multiple periods, the pricing problem becomes dynamic. Firms will discount profits k periods into the future by $M_{t,t+k}\theta_p^k$, where $M_{t,t+k} = \beta^k \frac{\lambda_{S,t+k}}{\lambda_{S,t}}$ is the stochastic discount factor, which follows from the fact that the firm is owned by the savers. The price setting problem reads

$$\begin{aligned} \max_{P_t(i)} \quad & E_t \sum_{k=0}^{\infty} (\beta\theta_p)^k \frac{\lambda_{S,t+k}}{\lambda_{S,t}} \left(\frac{P_t(i)}{P_{t+k}} y_{t+k}(i) - mc_{t+k} y_{t+k}(i) \right) \\ \text{s.t.} \quad & \left\{ y_{t+k}(i) = \left(\frac{P_t(i)}{P_{t+k}} \right)^{-\epsilon_p} y_{d,t+k} \right\}_{k=0}^{\infty}. \end{aligned}$$

The FOC reads

$$E_t \sum_{k=0}^{\infty} (\beta\theta_p)^k \lambda_{S,t+k} \left((1-\epsilon_p) P_{t+k}^{\epsilon_p - 1} y_{d,t+k} + \epsilon_p \, mc_{t+k} P_t(i)^{-1} P_{t+k}^{\epsilon_p} y_{d,t+k} \right) = 0.$$

By rearranging, we obtain

$$P_t(i) = \frac{\epsilon_p}{\epsilon_p - 1} \frac{E_t \sum_{k=0}^{\infty} (\beta\theta_p)^k \lambda_{S,t+k} mc_{t+k} P_{t+k}^{\epsilon_p} y_{d,t+k}}{E_t \sum_{k=0}^{\infty} (\beta\theta_p)^k \lambda_{S,t+k} P_{t+k}^{\epsilon_p - 1} y_{d,t+k}}.$$

Note that nothing on the RHS depends on i. Thus, all firms will choose the same reset price $P_t^* = P_t(i)$.

We can write the optimal price more compactly as

$$P_t^* = \frac{\epsilon_p}{\epsilon_p - 1} \frac{X_{1,t}}{X_{2,t}}$$

with

$$X_{1,t} = E_t \sum_{k=0}^{\infty} (\beta\theta_p)^k \lambda_{S,t+k} mc_{t+k} P_{t+k}^{\epsilon_p} y_{d,t+k}$$
$$X_{2,t} = E_t \sum_{k=0}^{\infty} (\beta\theta_p)^k \lambda_{S,t+k} P_{t+k}^{\epsilon_p - 1} y_{d,t+k}.$$

We can also write the X's recursively

$$X_{1,t} = \lambda_{S,t} mc_t P_t^{\epsilon_p} y_{d,t} + \beta\theta_p E_t X_{1,t+1}$$
$$X_{2,t} = \lambda_{S,t} P_t^{\epsilon_p - 1} y_{d,t} + \beta\theta_p E_t X_{2,t+1}.$$ [8]

Let us now rewrite these expressions in terms of inflation (as the price level may be non-stationary). Define $x_{1,t} = \frac{X_{1,t}}{P_t^{\epsilon_p}}$ and $x_{2,t} = \frac{X_{2,t}}{P_t^{\epsilon_p - 1}}$. Thus, we have

$$x_{1,t} = \lambda_{S,t} mc_t y_{d,t} + \beta\theta_p E_t x_{1,t+1} \Pi_{t+1}^{\epsilon_p}$$
$$x_{2,t} = \lambda_{S,t} y_{d,t} + \beta\theta_p E_t x_{2,t+1} \Pi_{t+1}^{\epsilon_p - 1}.$$

The reset price equation then writes

$$P_t^* = \frac{\epsilon_p}{\epsilon_p - 1} P_t \frac{x_{1,t}}{x_{2,t}}$$
$$\Rightarrow \Pi_t^* = \frac{\epsilon_p}{\epsilon_p - 1} \Pi_t \frac{x_{1,t}}{x_{2,t}},$$

where we define reset price inflation as $\Pi_t^* = \frac{P_t^*}{P_{t-1}}$.

Exploiting the Calvo assumption, we can write the aggregate price index as

$$\Pi_t^{1-\epsilon_p} = (1 - \theta_p)(\Pi_t^*)^{1-\epsilon_p} + \theta_p.$$

[8] If $\theta_p = 0$, then this would reduce to

$$P_t^* = \underbrace{\frac{\epsilon_p}{\epsilon_p - 1}}_{\mathcal{M}} P_t \, mc_t,$$

i.e. the optimal price would be a fixed markup over nominal marginal cost.

By way of summary, optimal behavior of firm i is characterized by

$$\frac{r_t k_t}{y_t} = \alpha(1-\nu)^{\frac{1}{\epsilon_y}} mc_t \left(\frac{e^{-\gamma s_t} a_t k_t^{\alpha} h_{y,t}^{1-\alpha}}{y_t} \right)^{\frac{\epsilon_y - 1}{\epsilon_y}} \tag{24}$$

$$\frac{w_t h_{y,t}}{y_t} = (1-\alpha)(1-\nu)^{\frac{1}{\epsilon_y}} mc_t \left(\frac{e^{-\gamma s_t} a_t k_t^{\alpha} h_{y,t}^{1-\alpha}}{y_t} \right)^{\frac{\epsilon_y - 1}{\epsilon_y}} \tag{25}$$

$$\frac{p_{e,t} e_{y,t}}{y_t} = \nu^{\frac{1}{\epsilon_y}} mc_t \left(\frac{e^{-\gamma s_t} e_{y,t}}{y_t} \right)^{\frac{\epsilon_y - 1}{\epsilon_y}} \tag{26}$$

$$\Pi_t^* = \frac{\epsilon_p}{\epsilon_p - 1} \Pi_t \frac{x_{1,t}}{x_{2,t}} \tag{27}$$

$$x_{1,t} = \lambda_{S,t} mc_t y_{d,t} + \beta \theta_p E_t x_{1,t+1} \Pi_{t+1}^{\epsilon_p} \tag{28}$$

$$x_{2,t} = \lambda_{S,t} y_{d,t} + \beta \theta_p E_t x_{2,t+1} \Pi_{t+1}^{\epsilon_p - 1} \tag{29}$$

$$\Pi_t^{1-\epsilon_p} = (1-\theta_p)(\Pi_t^*)^{1-\epsilon_p} + \theta_p \tag{30}$$

$$y_t(i) = e^{-\gamma s_t} \left[(1-\nu)^{1/\epsilon_y} \left(a_t k_t(i)^{\alpha} h_{y,t}(i)^{1-\alpha} \right)^{(\epsilon_y - 1)/\epsilon_y} + \nu^{1/\epsilon_y} \left(e_{y,t}(i) \right)^{(\epsilon_y - 1)/\epsilon_y} \right]^{\epsilon_y/(\epsilon_y - 1)}$$

The aggregate production is given by

$$\begin{aligned} y_t &= \int_0^1 y_t(i) di \\ &= \int_0^1 e^{-\gamma s_t} \left[(1-\nu)^{1/\epsilon_y} \left(a_t k_t(i)^{\alpha} h_{y,t}(i)^{1-\alpha} \right)^{(\epsilon_y - 1)/\epsilon_y} + \nu^{1/\epsilon_y} \left(e_{y,t}(i) \right)^{(\epsilon_y - 1)/\epsilon_y} \right]^{\epsilon_y/(\epsilon_y - 1)} di \\ \Rightarrow y_t &= e^{-\gamma s_t} \left[(1-\nu)^{1/\epsilon_y} \left(a_t k_t^{\alpha} h_{y,t}^{1-\alpha} \right)^{(\epsilon_y - 1)/\epsilon_y} + \nu^{1/\epsilon_y} \left(e_{y,t} \right)^{(\epsilon_y - 1)/\epsilon_y} \right]^{\epsilon_y/(\epsilon_y - 1)} \\ &= \int_0^1 \left(\frac{P_t(i)}{P_t} \right)^{-\epsilon_p} di y_{d,t} = \Delta_t y_{d,t}, \end{aligned} \tag{31}$$

where we have exploited the fact that factors are hired in the same proportion and plugged in for the demand function. Note that there is a wedge between aggregate output and aggregate demand. The intuition is that with Calvo pricing, firms charging prices in different periods will generally have different prices, which implies that the model features price dispersion.

We can rewrite the dispersion term in terms of inflation making use of the Calvo assumption. We have

$$\Delta_t = (1-\theta_p)(\Pi_t^*)^{-\epsilon_p} \Pi_t^{\epsilon_p} + \theta_p \Pi_t^{\epsilon_p} \Delta_{t-1}. \tag{32}$$

Firms profits are

$$d_t = \int_0^1 \frac{P_t(i)}{P_t} y_t(i) di - mc_t \int_0^1 y_t(i) di.$$

Plugging in the demand function gives

$$d_t = y_{d,t} P_t^{\epsilon_p - 1} \int_0^1 P_t(i)^{1-\epsilon_p} di - mc_t y_{d,t} \int_0^1 \left(\frac{P_t(i)}{P_t} \right)^{-\epsilon_p} di.$$

Now since $P_t^{1-\epsilon_p} = \int_0^1 P_t(i)^{1-\epsilon_p} di$, this reduces to

$$d_t = y_{d,t} - mc_t y_{d,t} \int_0^1 \left(\frac{P_t(i)}{P_t} \right)^{-\epsilon_p} di$$

Thus, we can write profits as

$$d_t = (1 - mc_t \Delta_t) y_{d,t}. \tag{33}$$

Further, note that

$$mc_t y_t = r_t k_t + p_{e,t} e_{y,t} + w_t h_{y,t}.$$

Thus, we can also write profits as

$$d_t = y_{d,t} - r_t k_t - p_{e,t} e_{y,t} - w_t h_{y,t}.$$

D.3. Climate block

Following Golosov et al. (2014), I model the current level of atmospheric carbon concentration as a function of current and past emissions:

$$s_t = \sum_{s=0}^{\infty} (1 - d_s) e_{t-s},$$

where $1 - d_s = (1 - \varphi_L)\varphi_0(1 - \varphi)^s$. Here, $1 - \varphi_0$ is the share of remaining emissions exiting the atmosphere immediately while φ_0 is the remaining share of emissions that decay over time at a geometric rate $1 - \varphi$. We can write this in recursive form as

$$s_t = (1 - \varphi) s_{t-1} + \varphi_0 e_t. \tag{34}$$

D.4. Fiscal and monetary policy

The government runs a balanced budget in every period, i.e. all transfers are financed by tax revenues. We consider the following transfer policy

$$\lambda \omega_{H,t} = \tau^d d_t + \tau^k r_t^K k_t + \mu \tau_t p_{e,t} e_t \tag{35}$$

$$(1-\lambda)\omega_{S,t} = (1-\mu)\tau_t p_{e,t} e_t. \tag{36}$$

The distribution of carbon tax revenues are governed by parameter μ. As the baseline, we assume that all carbon revenues are obtained by the savers, i.e. $\mu = 0$. Later, we will experiment with alternative transfer policies.[9]

Carbon taxes τ_t are set according to the following rule:

$$\tau_t = (1-\rho_\tau)\tau + \rho_\tau \tau_{t-1} + \epsilon_{\tau,t}. \tag{37}$$

Finally, we assume that there is a monetary authority that conducts monetary policy according to the following Taylor rule (in log-linear form):

$$\hat{r}_t^b = \rho_r \hat{r}_{t-1}^b + (1-\rho_r)\phi_\pi \hat{\pi}_{T,t} + \epsilon_{mp,t}, \tag{38}$$

where $\hat{\pi}_{T,t}$ is headline consumer price inflation: $\hat{\pi}_{T,t} = \lambda \hat{\pi}_{H,t} + (1-\lambda)\hat{\pi}_{S,t}$ with $\Pi_{H,t} = \frac{p_{H,t}}{p_{H,t-1}}\Pi_t$ and $\Pi_{S,t} = \frac{p_{S,t}}{p_{S,t-1}}\Pi_t$.

D.5. Aggregation and market clearing

Because capital is only held by S, we have that $(1-\lambda)k_{S,t} = k_t$ and $(1-\lambda)i_{S,t} = i_t$. Because bonds are in zero net supply, we have $z_{S,t} = z_{H,t} = b_{S,t} = b_{H,t} = 0$.

Aggregate total, non-energy, and energy consumption are given by $x_t = \lambda x_{H,t} + (1-\lambda)x_{S,t}$, $c_t = \lambda c_{H,t} + (1-\lambda)c_{S,t}$, and $e_{c,t} = \lambda e_{H,t} + (1-\lambda)e_{S,t}$, respectively. Labor market clearing requires $\lambda h_{H,t} + (1-\lambda)h_{S,t} = h_{y,t} + h_{e,t}$. The energy market clears if $e_t = e_{c,t} + e_{y,t}$. Finally, goods market clearing requires that

$$c_t + i_t = y_{d,t}. \tag{39}$$

To derive this, we multiply the households budget constraints by their shares and sum over them:

[9] Furthermore, we assume that $\tau^d = \tau^k = 0$. However, the tax scheme can be used to equalize incomes if $\tau^d = \tau^k = \mu = \lambda$.

$$\lambda p_{H,t} x_{H,t} + (1-\lambda)(p_{S,t} x_{S,t} + i_{S,t} + b_{S,t+1}) = \lambda(w_t h_{H,t} + \omega_{H,t}) + (1-\lambda)\left(w_t h_{S,t} + \frac{R^b_{t-1}}{\Pi_t} b_{S,t} + (1-\tau^k) r_t k_{S,t} + \frac{(1-\tau^d) d_t}{1-\lambda} + \omega_{S,t}\right)$$

$$c_t + i_t + p_{e,t} e_{c,t} = w_t h_t + r_t k_t + \tau_t p_{e,t} e_t + d_t$$

$$c_t + i_t + p_{e,t} e_{c,t} = w_t h_t + r_t k_t + \tau_t p_{e,t} e_t + y_{d,t} - r_t k_t - w_t h_{y,t} - p_{e,t} e_{y,t}$$

$$c_t + i_t = w_t h_{y,t} + w_t h_{e,t} + \tau_t p_{e,t} e_t + y_{d,t} - w_t h_{y,t} - p_{e,t} e_t$$

$$c_t + i_t = (1-\tau_t) p_{e,t} e_t + \tau_t p_{e,t} e_t + y_{d,t} - p_{e,t} e_t$$

$$c_t + i_t = y_{d,t}.$$

D.6. Equilibrium

A general equilibrium of this economy is defined as a sequence of quantities $\mathcal{Q} = \{x_t, x_{S,t}, x_{H,t}, c_t, c_{S,t}, c_{H,t}, e_{c,t}, e_{S,t}, e_{H,t}, i_t, k_{t+1}, y_t, y_{d,t}, h_{H,t}, h_{S,t}, h_{y,t}, h_{e,t}, e_{y,t}, mc_t, e_t, s_t, \tau_t, \omega_{H,t}, d_t, \Delta_t, x_{1,t}, x_{2,t}\}_{t=0}^{\infty}$, a sequence of prices $\mathcal{P} = \{\lambda_{S,t}, w_t, r_t, p_{e,t}, p_{S,t}, p_{H,t}, R^b_t, \Pi_t, \Pi^*_t, \Pi_{e,t}, \Pi_{T,t}\}_{t=0}^{\infty}$, and a sequence of forcing variables $\mathcal{F} = \{a_t, a_{e,t}, \epsilon_{\tau,t}, \epsilon_{mp,t}\}_{t=0}^{\infty}$ such that

1. Given a sequence of prices $\mathcal{P}$, and a forcing sequence $\mathcal{F}$, the sequence of quantities $\mathcal{Q}$ solves the households' and the firms' problems.

2. Given a sequence of quantities $\mathcal{Q}$ and a sequence of forcing variables $\mathcal{F}$, the sequence of prices $\mathcal{P}$ clears all markets.

The equilibrium is characterized by the following set of equations:

Table D.1: Summary of Equilibrium Conditions

1:	Labor supply, S	$\frac{x_{S,t}^{-\sigma}}{p_{S,t}} w_t = \psi_S h_{S,t}^{\theta}$
2:	Non-energy demand, S	$c_{S,t} = a_{S,c} \left(\frac{1}{p_{S,t}}\right)^{-\epsilon_x} x_{S,t}$
3:	Energy demand, S	$e_{S,t} = a_{S,e} \left(\frac{p_{e,t}}{p_{S,t}}\right)^{-\epsilon_x} x_{S,t}$
4:	Shadow value of wealth	$p_{S,t}\lambda_{S,t} = x_{S,t}^{-\sigma}$
5:	Bonds Euler equation, S	$\frac{x_{S,t}^{-\sigma}}{p_{S,t}} = \beta E_t \left[\frac{R_t^b}{\Pi_{t+1}} \left(s \frac{x_{S,t+1}^{-\sigma}}{p_{S,t+1}} + (1-s) \frac{x_{H,t+1}^{-\sigma}}{p_{H,t+1}}\right)\right]$
6:	Investment Euler equation, S	$q_t = \beta E_t \left[\frac{\lambda_{S,t+1}}{\lambda_{S,t}} \left((1-\tau^k) r_{t+1} + q_{t+1} \left(1 - \delta - \frac{\varphi_k}{2} \left(\frac{i_{t+1}}{k_{t+1}} - \delta\right)^2 + \varphi_k \left(\frac{i_{t+1}}{k_{t+1}} - \delta\right) \frac{i_{t+1}}{k_{t+1}}\right)\right)\right]$
7:	Tobin's q	$1 = q_t \left(1 - \varphi_k \left(\frac{i_t}{k_t} - \delta\right)\right)$
8:	Capital accumulation	$k_{t+1} = i_t - \frac{\varphi_k}{2} \left(\frac{i_t}{k_t} - \delta\right)^2 k_t + (1-\delta) k_t$
9:	Final good price index, S	$p_{S,t} = \left(a_{S,c} + a_{S,e} p_{e,t}^{1-\epsilon_x}\right)^{\frac{1}{1-\epsilon_x}}$
10:	Labor supply, H	$\frac{x_{H,t}^{-\sigma}}{p_{H,t}} w_t = \psi_H h_{H,t}^{\theta}$
11:	Non-energy demand, H	$c_{H,t} = a_{H,c} \left(\frac{1}{p_{H,t}}\right)^{-\epsilon_x} x_{H,t}$
12:	Energy demand, H	$e_{H,t} = a_{H,e} \left(\frac{p_{e,t}}{p_{H,t}}\right)^{-\epsilon_x} x_{H,t}$
13:	Consumption, H	$p_{H,t} x_{H,t} = w_t h_t + \omega_{H,t}$
14:	Final good price index, H	$p_{H,t} = \left(a_{H,c} + a_{H,e} p_{e,t}^{1-\epsilon_x}\right)^{\frac{1}{1-\epsilon_x}}$
15:	Capital demand non-energy firm	$\frac{r_t k_t}{y_t} = \alpha (1-\nu)^{\frac{1}{\epsilon_y}} mc_t \left(\frac{e^{-\gamma s_t} a_t k_t^{\alpha} h_{y,t}^{1-\alpha}}{y_t}\right)^{\frac{\epsilon_y - 1}{\epsilon_y}}$
16:	Labor demand non-energy firm	$\frac{w_t h_{y,t}}{y_t} = (1-\alpha)(1-\nu)^{\frac{1}{\epsilon_y}} mc_t \left(\frac{e^{-\gamma s_t} a_t k_t^{\alpha} h_{y,t}^{1-\alpha}}{y_t}\right)^{\frac{\epsilon_y - 1}{\epsilon_y}}$
17:	Energy demand non-energy firm	$\frac{p_{e,t} e_{y,t}}{y_t} = \nu^{\frac{1}{\epsilon_y}} mc_t \left(\frac{e^{-\gamma s_t} e_{y,t}}{y_t}\right)^{\frac{\epsilon_y - 1}{\epsilon_y}}$
18:	Reset price	$\Pi_t^* = \frac{\epsilon_p}{\epsilon_p - 1} \Pi_t \frac{x_{1,t}}{x_{2,t}}$
19-20:	Auxiliary terms	$x_{1,t} = \lambda_t mc_t y_{d,t} + \beta \theta_p E_t x_{1,t+1} \Pi_{t+1}^{\epsilon_p}$
		$x_{2,t} = \lambda_t y_{d,t} + \beta \theta_p E_t x_{2,t+1} \Pi_{t+1}^{\epsilon_p - 1}$
21:	Aggregate inflation	$\Pi_t^{1-\epsilon_p} = (1-\theta_p)(\Pi_t^*)^{1-\epsilon_p} + \theta_p$
22:	Price dispersion	$\Delta_t = (1-\theta_p)(\Pi_t^*)^{-\epsilon_p} \Pi_t^{\epsilon_p} + \theta_p \Pi_t^{\epsilon_p} \Delta_{t-1}$
23:	Aggregate demand non-energy	$y_{d,t} \Delta_t = y_t$
24:	Prod. function non-energy firm	$y_t = e^{-\gamma s_t} \left[(1-\nu)^{\frac{1}{\epsilon_y}} \left(a_t k_t^{\alpha} h_{y,t}^{1-\alpha}\right)^{\frac{\epsilon_y - 1}{\epsilon_y}} + \nu^{\frac{1}{\epsilon_y}} \left(e_{y,t}\right)^{\frac{\epsilon_y - 1}{\epsilon_y}}\right]^{\frac{\epsilon_y}{\epsilon_y - 1}}$
25:	Energy supply	$(1-\tau_t) p_{e,t} e_t = w_t h_{e,t}$
26:	Production function energy firm	$e_t = a_{e,t} h_{e,t}$
27:	Carbon emissions	$s_t = (1-\varphi) s_{t-1} + \varphi_0 e_t$
28:	Aggregate total consumption	$x_t = \lambda x_{H,t} + (1-\lambda) x_{S,t}$
29:	Aggregate non-energy consumption	$c_t = \lambda c_{H,t} + (1-\lambda) c_{S,t}$
30.	Aggregate energy consumption	$e_{c,t} = \lambda e_{H,t} + (1-\lambda) e_{S,t}$
31:	Labor market clearing	$\lambda h_{H,t} + (1-\lambda) h_{S,t} = h_{y,t} + h_{e,t}$

32:	Energy market clearing	$e_t = e_{c,t} + e_{y,t}$
33:	Goods market clearing	$c_t + i_t = y_{d,t}$
34:	Tax schedule	$\tau_t = (1-\rho_\tau)\tau + \rho_\tau \tau_{t-1} + \epsilon_{\tau,t}$
35:	Transfers, H	$\lambda \omega_{H,t} = \tau^d d_t + \tau^k r_t^K k_t + \mu \tau_t p_{e,t} e_t$
36:	Dividends	$d_t = (1 - mc_t \Delta_t) y_{d,t}$
37:	Taylor rule	$\hat{r}_t^b = \rho_r \hat{r}_{t-1}^b + (1-\rho_r)(\phi_\pi \hat{\pi}_{T,t}) + \epsilon_{mp,t}$
38:	Headline inflation	$\hat{\pi}_{T,t} = \lambda \hat{\pi}_{H,t} + (1-\lambda)\hat{\pi}_{S,t}$
39:	Inflation, p_H	$\Pi_{H,t} = \frac{p_{H,t}}{p_{H,t-1}} \Pi_t$
40:	Inflation, p_S	$\Pi_{S,t} = \frac{p_{S,t}}{p_{S,t-1}} \Pi_t$

D.7. Calibration

We parameterize the model as follows. The time period is a quarter. The discount factor β takes the standard value 0.99, which implies an annualized steady-state interest rate of 4 percent. The intertemporal elasticity of substitution $1/\sigma$ and the labor supply elasticity $1/\theta$ are set to 1. These are standard values in the literature.

The labor weight in the utility function, φ_i is set such that steady-state hours worked h_i are normalized to one. I calibrate the share of hand-to-mouth λ to 25 percent, corresponding to the low-income threshold used in the LCFS. Such a share is also in line with the estimates of hand-to-mouth households in Kaplan, Violante, and Weidner (2014). Idiosyncratic risk is calibrated to $1 - s = 0.04$, as in Bilbiie (2020). The distribution parameters $a_{H,e}$ and $a_{S,e}$ are set to match the energy expenditure shares of 9.5 percent for the hand-to-mouth and 6.5 percent for the savers as observed in the LCFS. Note that the elasticity of substitution ϵ_x is the same as the own price elasticity in this model. I calibrate ϵ_x to 0.05 for hand-to-mouth and 0.275 for savers, as my empirical evidence points to a lower elasticity for constrained households. The implied average elasticity is consistent with Labandeira, Labeaga, and López-Otero (2017) who perform a meta analysis on the price elasticity of energy demand and find an average short-run elasticity of around 0.21.

Turning to the production side, I set the depreciation rate δ to 0.025, implying an annual depreciation on capital of 10 percent. The capital adjustment cost parameter is set to $\varphi_k = 4$, which implies an elasticity of investment to Tobin's marginal q of 10. I set α to 0.3, implying a steady-state capital share of around 70 percent (see e.g. Smets and Wouters, 2003). Using data on non-household energy consumption and energy prices in the EU, I estimate a energy share of around 7 percent. To approximate that share, I thus set $\nu = 0.07$. The elasticity of substitution between energy and capital/labor is set to 0.21, drawing again on the evidence in Labandeira, Labeaga, and López-Otero (2017). The elasticity of sub-

stitution between non-energy varieties is assumed to be 6, which is a standard value and implies a steady-state markup of 20 percent, consistent with the evidence in Christopoulou and Vermeulen (2012). The Calvo parameter θ_p is set to 0.825, which implies an average price duration of 5-6 quarters, in line with the empirical estimates in Alvarez et al. (2006). These parameter choices imply a relatively flat Phillips curve with a slope of 0.04.

For the climate block, I rely on the values in Golosov et al. (2014). I abstract from uncertainty about the damage parameter and use the deterministic, long-run value from Golosov et al. (2014). Note, however, that carbon emissions in my model are in arbitrary units. Thus, following Heutel (2012) I scale the damage parameter to make the increase in output damages from doubling the steady-state carbon stock consistent with the projected increase in damages from doubling CO2 levels in 2005. Turning to the carbon cycle, note that the excess carbon has a half-life of about 300 years (Archer, 2005). This implies a value of $1 - \varphi = 0.9994$.[10] Furthermore, according to the 2007 IPCC reports, about half of the CO2 pulse to the atmosphere is removed after a time scale of 30 years. This implies that $\varphi_0 = \frac{0.5}{(1-\varphi)^{120}} = 0.5359$.

Turning to fiscal and monetary policy, I compute the steady-state carbon tax as the implied tax rate implied by the average EUA price which is around 3.9 percent (the average real EUA price as a share of gross electricity prices in emission units). The persistence of the tax shock is set to 0.85, which is broadly consistent with the shock persistence estimated in the external instruments VAR. Finally, the Taylor rule coefficient on inflation is set to 1.5, and interest smoothing is assumed to be 0.8. These values are standard in the literature.

All other taxes are assumed to be zero in the baseline case, later we will use them to equalize the income incidence. Furthermore, we assume that all carbon tax revenues accrue to the savers, $\mu = 0$, motivated by the fact that there is no redistribution scheme in the current EU ETS in place. The calibration is summarized in Table D.2.

[10] From the carbon cycle, we have $E_t s_{t+h} = (1-\varphi)^h s_t = 0.5 s_t$. Thus, we impose $(1-\varphi)^{1200} = 0.5$ to get φ.

Table D.2: Calibration

Parameter	Description	Value	Target/Source/Comments
β	Discount factor	0.99	Standard value
$1/\sigma$	Intertemporal elasticity of substitution	1	Standard value
$1/\theta$	Labor supply elasticity	1	Standard value
λ	Share of hand-to-mouth	0.25	Share of low-income households, LCFS
$1-s$	Probability of becoming H	0.04	Bilbiie (2020)
$a_{H,e}$	Distribution parameter H	0.078	Energy share of 9.5%, LCFS
$a_{S,e}$	Distribution parameter S	0.056	Energy share of 6.5%, LCFS
ϵ_{xH}	Elasticity of substitution energy/non-energy H	0.05	LCFS, Labandeira, Labeaga, and López-Otero (2017)
ϵ_{xS}	Elasticity of substitution energy/non-energy S	0.275	LCFS, Labandeira, Labeaga, and López-Otero (2017)
ϵ_y	Elasticity of substitution energy/non-energy firms	0.21	Labandeira, Labeaga, and López-Otero (2017)
δ	Depreciation rate	0.025	Standard value
φ_k	Capital adjustment costs	4	Standard value
α	Capital returns-to-scale	0.3	Standard value
ν	Energy returns-to-scale	0.07	Steady-state energy share of $\approx$ 7%; Eurostat
ϵ_p	Price elasticity	6	Steady-state markup of 20%
θ_p	Calvo parameter	0.825	Average price duration of 5-6 quarters
γ	Climate damage parameter	$5.3 * 10^{-5}$	Golosov et al. (2014)
φ_0	Emissions staying in atmosphere	0.5359	Golosov et al. (2014)
$1-\varphi$	Emissions decay parameter	0.9994	Golosov et al. (2014)
ϕ_π	Taylor rule coefficient inflation	1.5	Standard value
ρ_r	Interest smoothing	0.8	Standard value
τ	Steady-state carbon tax	0.039	Implied tax rate from average EUA price
ρ_τ	Persistence carbon tax shock	0.85	Persistence in the data

D.8. Steady state and model solution

We assume that $a = a_e = 1$ in steady state and we normalize ψ_i such that $h_i = 1$. Furthermore, τ is calibrated. Finally, we assume that there is zero inflation in steady state, i.e. $\Pi = \Pi_T = 1$. From the definition of aggregate inflation and the price dispersion, this implies $\Pi^* = 1$, $\Delta = 1$ and $y_d = y$.

From the investment Euler equation, we have

$$r = \frac{\frac{1}{\beta} - 1 + \delta}{1 - \tau^k}.$$

From the bonds Euler, we get

$$R^b = \frac{1}{\beta}.$$

From the reset price, we get

$$mc = \frac{\epsilon_p - 1}{\epsilon_p}.$$

From Tobin's q, we have $q = 1$.

To solve for the steady state, we guess k and e. From [27], we get s.[11] From [26], we get h_e. From [31], we get h_y. From [15] we get y. From [24], we get e_y. From [32], we get e_c. From [17], we get p_e. From [16], we get w. From [8], we get i. From [33], we get c. From [9], we get p_S:

$$\begin{aligned}
p_S &= \left(a_{S,c} + a_{S,e} p_e^{1-\epsilon_x}\right)^{\frac{1}{1-\epsilon_x}} \\
&= \left(1 - \omega_{S,e} p_e^{\epsilon_x - 1} p_S^{1-\epsilon_x} + \omega_{S,e} p_S^{1-\epsilon_x}\right)^{\frac{1}{1-\epsilon_x}} \\
&= p_S \left(p_S^{\epsilon_x - 1} - \omega_{S,e} p_e^{\epsilon_x - 1} + \omega_{S,e}\right)^{\frac{1}{1-\epsilon_x}} \\
\Rightarrow 1 &= p_S^{\epsilon_x - 1} - \omega_{S,e} p_e^{\epsilon_x - 1} + \omega_{S,e} \\
p_S &= \left(1 + \omega_{S,e} p_e^{\epsilon_x - 1} - \omega_{S,e}\right)^{\frac{1}{\epsilon_x - 1}}.
\end{aligned}$$

From this we then have $a_{S,e} = \omega_{S,e} \left(\frac{p_e}{p_S}\right)^{\epsilon_x - 1}$ and $a_{S,c} = 1 - a_{S,e}$. Similarly we get from [14] p_H and $a_{H,e}$ and $a_{H,c}$. From [36], we get d. From [35], we get ω_H. From [13], we get x_H. From [11], we get c_H. From [12], we get e_H. From [29], we get c_S. From [30], we get e_S. From [3], we get x_S. From [4], we get λ. From [1], we get ψ_S and from [10], we get ψ_H. From [19]-[20], we get the values of the auxiliary terms x_1 and x_2.

Then we optimize such that [2] and [25] hold.

To solve the model, we log-linearize the equilibrium equations around the deterministic steady state and solve for a set of linearized policy functions using Dynare.

[11] The equation numbers here refer to the equations in Table D.1.

References Appendix

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