The unequal economic consequences of carbon pricing

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Motivation

The looming climate crisis

- Looming **climate crisis** put climate change at **top** of the **global policy agenda**
- **Carbon pricing** increasingly used as a tool to mitigate climate change **but:**
- **Little known** about effects on **emissions** and the **economy** in practice
    - Effectiveness?
    - Short-term economic costs?
    - Distributional consequences?

This paper

- New evidence from the European **Emissions Trading Scheme** (**ETS**), the **largest** carbon market in the world
- Exploit **institutional features** of the EU ETS and **high-frequency data** to estimate **aggregate** and **distributional** effects of **carbon pricing**
  - Cap-and-trade system: **Market price** for carbon, liquid **futures markets**
  - Regulations in the market **changed** considerably over time
  - Isolate **exogenous** variation by measuring carbon price change in **tight window** around **policy events**
  - Use as **instrument** to estimate dynamic causal effects of a **carbon policy shock**

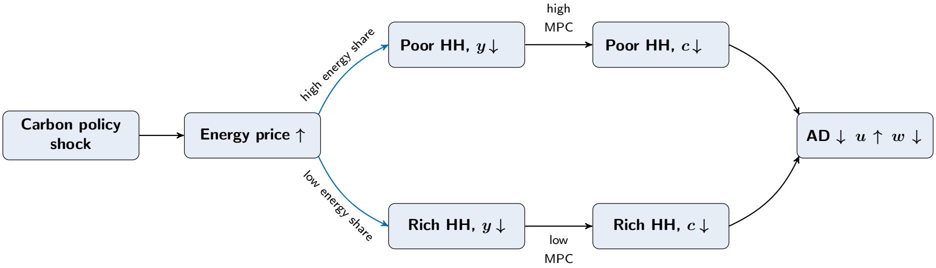
Main results

- Carbon policy has **significant** effects on emissions and the economy
- A shock **tightening** the **carbon pricing regime** leads to
  - a significant **increase in energy prices**, persistent **fall in emissions** and uptick in green innovation
  - not without **cost**: **economic activity falls**, consumer prices increase
  - costs **not** borne **equally** across society: **poor** lower their consumption significantly, **rich** barely affected

Main results

- **Poor** not only more exposed because of **higher energy share**, also face a stronger **fall** in **income**
  - Fall in **incomes** concentrated in **demand-sensitive sectors**; less heterogeneity across sectors' energy intensity
  - Poorer households **predominantly** work in demand-sensitive sectors but are underrepresented in energy-intensive sectors

Main results



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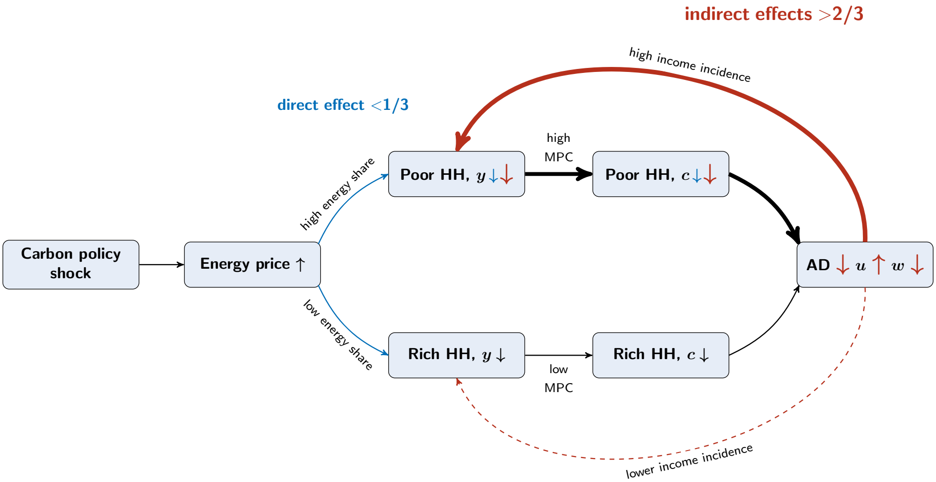


Main results

- **Indirect effects** via income and employment are **key** for the transmission
    - account for over **2/3** of the aggregate effect on consumption
- **Climate-economy model** with **heterogeneity** in energy shares, income incidence and MPCs can account for these facts
    - **targeted fiscal policy** can reduce **economic costs** of carbon pricing **without** compromising **emission reductions**

Related literature

- **Effects of carbon pricing on emissions, activity, inequality**:
  Theory: Nordhaus 2007; Golosov et al. 2014; McKibbin, Morris, and Wilcoxen 2014; Goulder and Hafstead 2018; Goulder et al. 2019; Rausch, Metcalf, and Reilly 2011; among many others
  Empirics: Lin and Li 2011; Martin, De Preux, and Wagner 2014; Andersson 2019; Pretis 2019; Metcalf 2019; Bernard, Kichian, and Islam 2018; Metcalf and Stock 2020*a*,*b*; Pizer and Sexton 2019; Ohlendorf et al. 2021
- **Macroeconomic effects of tax changes**: Blanchard and Perotti 2002; Romer and Romer 2010; Mertens and Ravn 2013; Cloyne 2013
- **High-frequency identification**: Kuttner 2001; Gürkaynak, Sack, and Swanson 2005; Gertler and Karadi 2015; Nakamura and Steinsson 2018; Känzig 2021
- **Heterogeneity and macro policy**: Johnson, Parker, and Souleles 2006; Kaplan and Violante 2014; Cloyne and Surico 2017; Bilbiie 2008; Auclert 2019; Patterson 2021

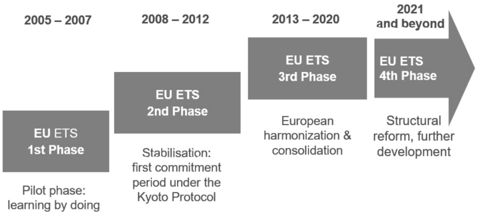
Identification

European carbon market

- Established in 2005, covers around **40%** of EU GHG emissions
- **Cap** on total emissions covered by the system, reduced each year
- **Emission allowances** (**EUA**) allocated within the cap
  - free allocation
  - auctions
  - international credits
- Companies must surrender **sufficient** EUAs to cover their yearly emissions
  - enforced with heavy fines
- Allowances are **traded** on secondary markets (spot and **futures** markets)

European carbon market

- Establishment of EU ETS followed **learning-by-doing** process
- Three main **phases**, **rules updated continuously**
  - address market issues
  - expand system
  - improve efficiency
- Lots of **regulatory events**



Carbon price

Figure 1: EUA price

Regulatory events

- Collected **comprehensive list** of **regulatory update** events
  - Decisions of European Commission
  - Votes of European Parliament
  - Judgments of European courts
- Of interest in this paper: regulatory news on the **supply of allowances**
  - National **allocation plans**
  - **Auctions**: timing and quantities
  - Use of international credits
- **Identified 126** relevant **events** from 2005-2019

▸ Details

High-frequency identification

- **Idea**: Identify carbon policy surprises from changes in EUA futures price in tight window around regulatory event

$$CPSurprise_{t,d} = \frac{F^{carbon}_{t,d} - F^{carbon}_{t,d-1}}{P^{elec}_{t,d-1}},$$

where $F_{t,d}$ is settlement price of the EUA front contract on event day d in month t and $P^{elec}_{t,d-1}$ is the wholesale electricity price on the day before

- Aggregate surprises to **monthly** series

$$CPSurprise_t = \begin{cases} CPSurprise_{t,d} & \text{if one event} \\ \sum_i CPSurprise_{t,d_i} & \text{if multiple events} \\ 0 & \text{if no event} \end{cases}$$

Carbon policy surprises

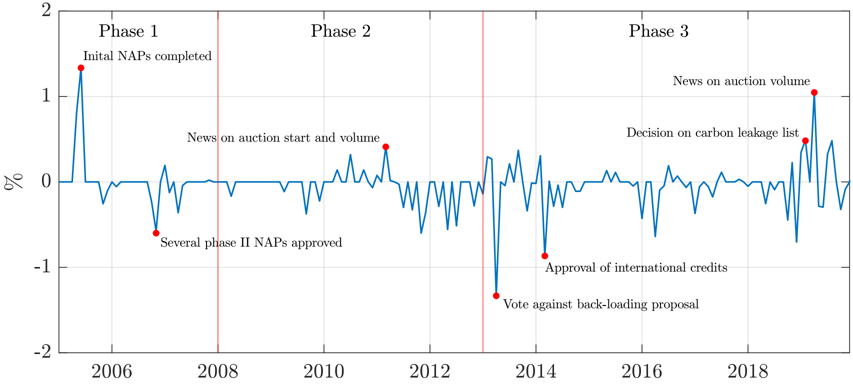


Figure 2: The carbon policy surprise series

▸ Diagnostics ▸ Alternative

Econometric framework

- **Carbon policy surprise series** has good properties but still imperfect measure

$\Rightarrow$ Use it as an external **instrument** to estimate dynamic causal effects on variables of interest (Stock and Watson, 2012; Mertens and Ravn, 2013) ▸ Details

  - robust to internal instrument approach (Ramey, 2011; Plagborg-Møller and Wolf, 2019) ▸ Details

- For estimation I rely on VAR techniques given the short sample ▸ More

Empirical specification

- 8 variable system, **euro area** data:
  - **Carbon block**: HICP[1] energy, total GHG emissions
  - **Macro-financial block**: headline HICP, industrial production, unemployment rate, policy rate, stock market index, oil price
- 6 lags as controls
- Estimation sample: 1999M1-2019M12

▸ Data

[1] HICP: Harmonized index of consumer prices

Results

First stage

- Weak instrument test by Montiel Olea and Pflueger (2013)
- Heteroskedastcitity-robust **F-statistic**: **17.43**
- **No** evidence for **weak instrument** problems

The aggregate effects of carbon pricing

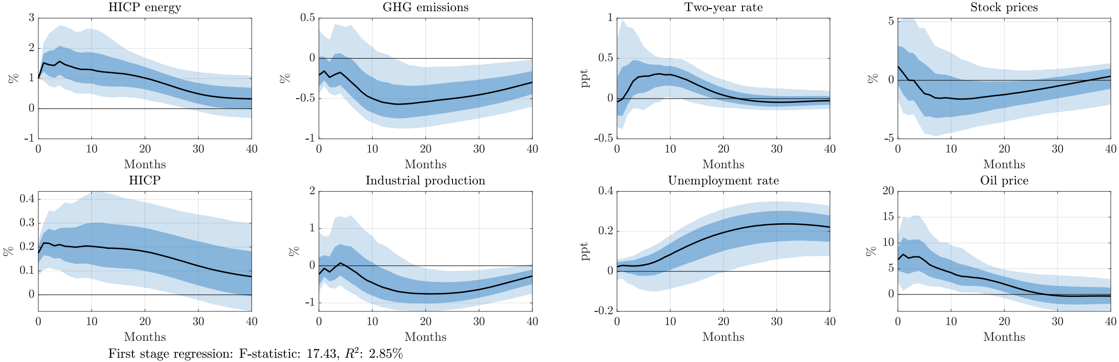


Figure 3: Responses to carbon policy shock, normalized to increase HICP energy by 1%

The solid line is the point estimate and the dark and light shaded areas are 68 and 90% confidence bands

▸ Internal instrument results ▸ Oil shock

The aggregate effects of carbon pricing

Restrictive **carbon policy shock** leads to

- strong, immediate **increase** in **energy prices**
- significant and persistent **fall** in **emissions**

This has **consequences** for the **economy**:

- Consumer prices increase ▸ More
- **Industrial production falls**, **unemployment rate rises**

⇒ **Trade-off** between reducing **emissions** and economic **activity**

▸ Historical importance

Wider effects and propagation channels

- **Energy prices** play an important role in the **transmission** of **carbon policy**
  - Suggests that **power sector** largely **passes through** emissions cost to energy prices, in line with previous evidence
- **Higher energy prices** can have significant effects on the economy via **direct** and **indirect** channels
- Better understand transmission by mapping out responses of wider range of macro and financial variables using local projections

$$y_{i,t+h} = \beta^i_{h,0} + \psi^i_h CPShock_t + \beta^i_{h,1} y_{i,t-1} + \ldots + \beta^i_{h,p} y_{i,t-p} + \xi_{i,t,h}$$

The transmission to the macroeconomy

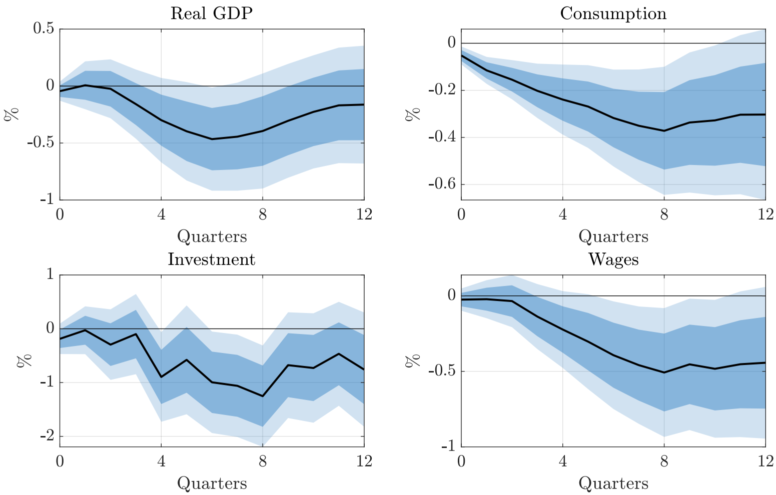


Figure 4: Effect on GDP and components

The transmission to the macroeconomy

- **Fall in GDP** similar to industrial production
- Looking at components, fall driven by **lower consumption and investment**
  - magnitudes much larger than can be accounted for by **direct effect** via energy prices
  - **indirect effects** via income seem to be important
- Little response of financial variables and uncertainty

The heterogeneous effects of carbon pricing

- Big debate on **energy poverty** amid Commission's 'Fit for 55' proposal
- Crucial to better understand the **distributional** effects crucial of **carbon pricing**
- Also helps to sharpen understanding of **transmission channels** at work

The heterogeneous effects of carbon pricing

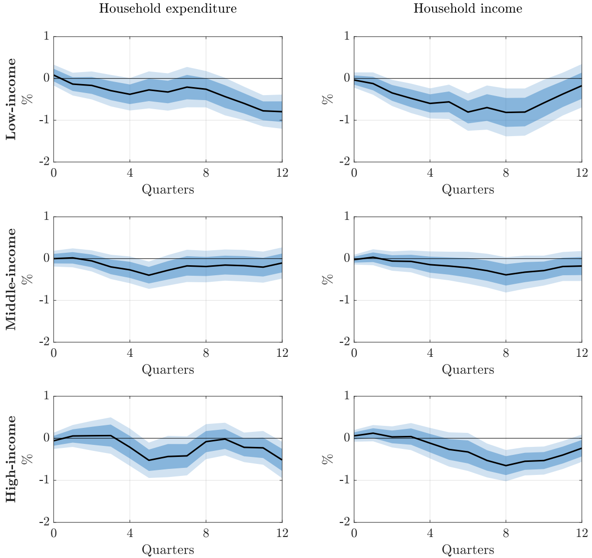
- Study **heterogeneous effects** of carbon pricing on **households**
- **Problem**: Household-level micro data not available at the EU level for long enough and regular sample
  - Focus on **UK** where high-quality micro data on **income** and **expenditure** is available
  - Check external validity using data for Denmark and Spain

Living costs and food survey

- **LCFS** is the major UK survey on household spending
  - provides detailed information on **expenditure, income**, and household **characteristics**
  - fielded every year but interview date allows to construct **quarterly** measures
- I compile a **repeated cross-section** spanning the period 1999 to 2019
  - each wave contains around 6,000 households, generating over 120,000 observations in total
- To estimate effects, I use a **grouping estimator** using **normal disposable income** as the grouping variable:
  - **Low-income**: Bottom 25%
  - **Middle-income**: Middle 50%
  - **High-income**: Top 25%

▸ Descriptive statistics

Heterogeneity by income group



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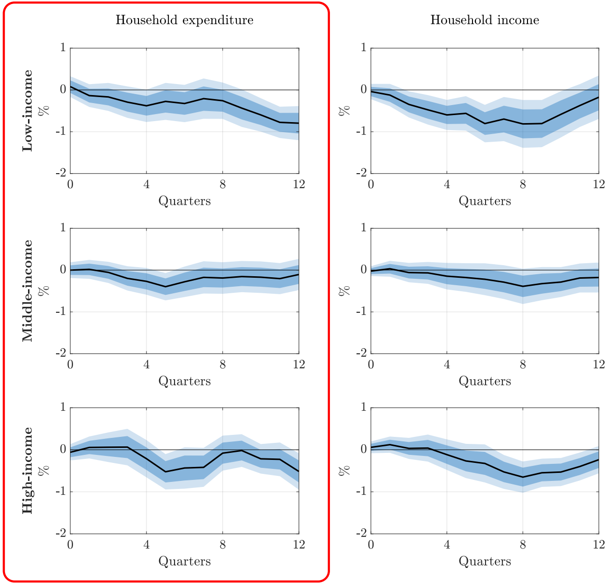

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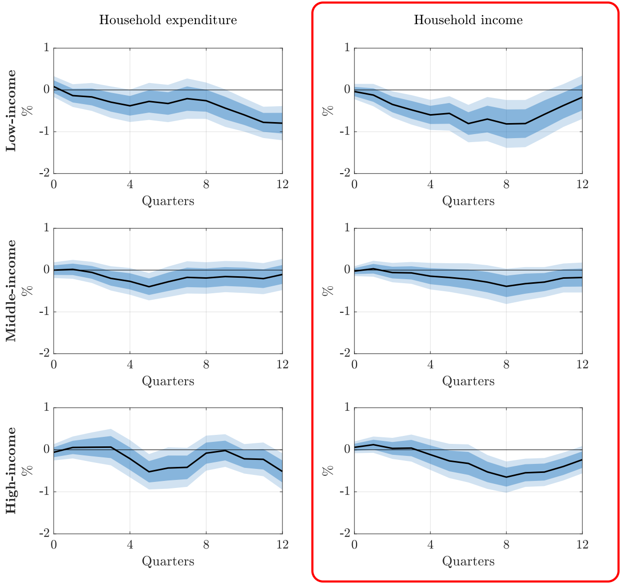

Heterogeneity by income group

- **Low-income** households **lower** their **consumption** significantly and persistently
- Response of **high-income** households barely significant
    - Low-income households are more exposed because of **higher energy share**
    - But also experience **stronger fall** in their **income**

▸ Energy/non-energy exp. ▸ Group differences ▸ More on grouping ▸ Other countries

Direct versus indirect effects

Table 1: Cumulative changes over impulse horizon in pounds

	Overall	By income group		
		Low-income	Middle-income	High-income
Expenditure				
Energy	23.88	28.36	22.53	22.11
	[-16.93, 64.69]	[8.21, 48.51]	[-18.02, 63.07]	[-0.96, 45.17]
Non-durables	-103.75	-134.76	-92.33	-95.60
excl. energy	[-212.38, 4.87]	[-241.21, -28.32]	[-192.67, 8.02]	[-279.87, 88.67]
Durables	-6.95	-2.92	-0.44	-23.99
	[-56.09, 42.20]	[-20.75, 14.92]	[-10.37, 9.50]	[-71.44, 23.45]
Income				
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Direct versus indirect effects

- Energy bill increases but **cannot** account for fall in expenditure, **indirect effects** via income seem important
  - account for **over 2/3** of the aggregate consumption response
- **Low-income** households face larger increase in energy bill and stronger fall in income, have to adjust their expenditure more
  - Policy heavily **regressive** after accounting for indirect effects
  - **Low-income** households account for $\sim$**30%** of the aggregate effect on consumption though they account for much smaller consumption share in normal times ($\sim$15%)

What drives the income response?

- Significant **heterogeneity** in income responses
- **Potential explanations**:
  - Heterogeneity in **labor income** because of differences in **employment sector** ▸ More
  - Differences in **income composition**: labor versus. **financial income** ▸ More

Policy implications

- Fiscal policies **targeted** to the **most affected** households can **reduce** the economic **costs** of climate change mitigation policy
- To the extent that energy demand is **inelastic**, this should **not compromise** emission reductions
  - Turns out to be particularly the case for low-income households ▸ IRFs

Model

- To study role of **redistributing** auction revenues, build a **climate-economy model** to use as a laboratory
- Climate-economy model with nominal rigidities and **household heterogeneity**
  - **Energy sector** producing energy/emissions using labor
  - **Non-energy NK sector** producing consumption good using energy, labor and capital
  - **Two households**: hand-to-mouth and savers differing in **energy expenditure shares**, **income incidence** and **MPCs**. Idiosyncratic risk as households switch between types
- Calibrated to match key micro and macro moments

▸ Model details

Redistributing carbon revenues

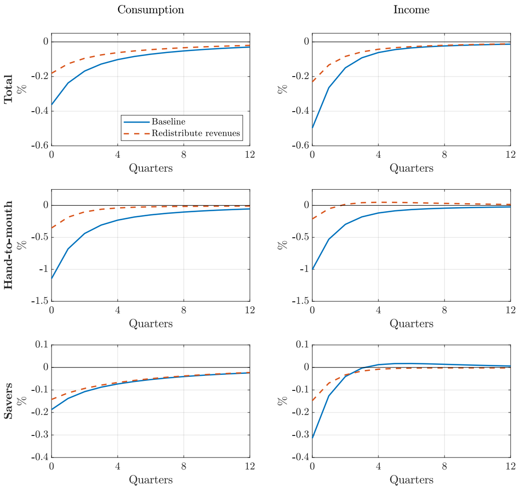

Figure 5: Responses to carbon tax shock

▸ More

Redistributing carbon revenues

- Model can **match** the estimated (peak) magnitudes in the data
  - **Heterogeneity** plays a crucial role,
  - In RA model implausibly high energy share needed to match magnitudes
- **Redistributing tax revenues** to hand-to-mouth can
  - **reduce inequality** and **attenuate** aggregate effect on **consumption**
  - while emissions only change little

More

Policy implications

- Especially relevant given recent surge in European carbon prices

- Distributional effects could threaten **public support** of the policy

▸ Suggestive evidence

Beyond the short term

- An often used argument for carbon prices is that it fosters **directed technological change**
- Use **patent data** from the EPO to study effect on patenting in climate change mitigation technologies

Effect on innovation

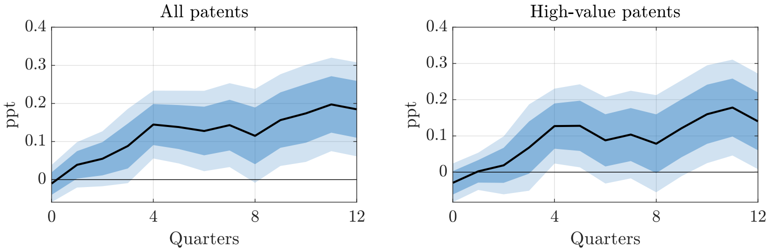

Figure 6: Share of low-carbon patents

- Significant increase in climate change mitigation patenting
- Key for longer-term **transition** to **low-carbon economy**

▸ Oil shock

Robustness

Check **robustness** with respect to

- **Selection of events**: robust to just using NAP/auction events, robust to dropping events in first phase or time of distress
- **Background noise**: robust to controlling for confounding news using a heteroskedasticity-based approach
- **Sample and specification choices**: robust to estimating on shorter sample, to lag order, and to using a smaller system to estimate effects

▸ Details

Conclusion

Conclusion

- New evidence on the **economic effects** of **carbon pricing** from the European carbon market
- Policy successful in **reducing emissions** and fostering green innovation
- But comes at **economic cost** that is **not borne equally** across society
  $\Rightarrow$ policy is quite **regressive** after accounting for **indirect** effects
- Targeted fiscal policy can reduce these costs without compromising emission reductions

Thank you!

Example events

Table 2: Regulatory update events (extract)

	Date	Event description	Type
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

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- **Narrative account**:
- **Autocorrelation**:
- **Forecastability**:
- **Orthogonality**:
- **Background noise**:

◂ Back ▸ More

Diagnostics

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- **Background noise**: ✓ Variance on event days over 6 times larger than on control days

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Autocorrelation

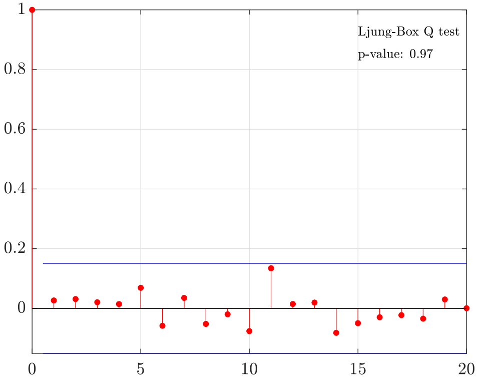

Figure 7: The autocorrelation function of the carbon policy surprise series

Forecastability

Table 3: 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

Orthogonality

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.

Background noise

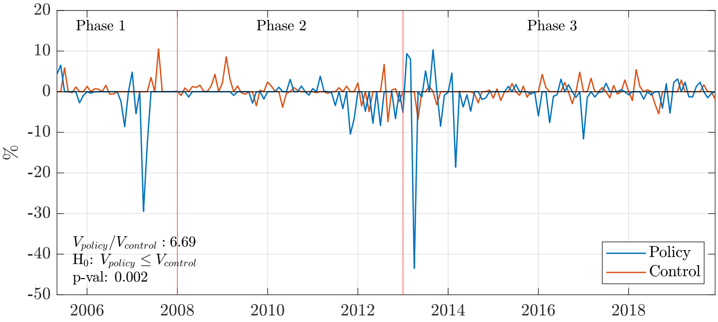

Figure 8: The carbon policy and the control series

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.

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Alternative carbon policy surprise series

$$CPSurprise_{t,d} = (log(F_{t,d}) - log(F_{t,d-1})) * 100$$

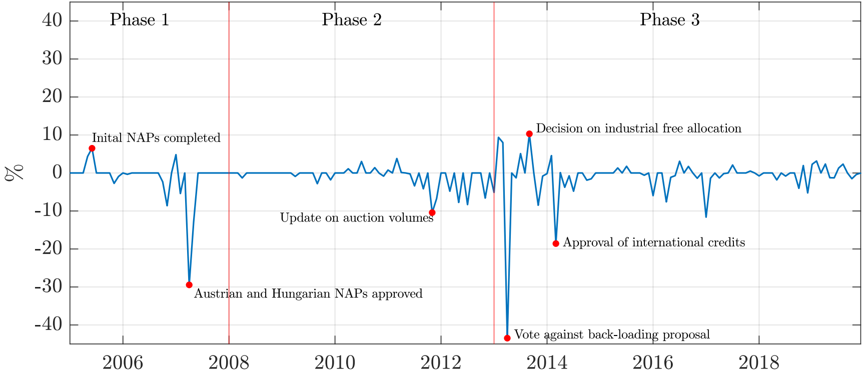

Figure 9: The carbon policy surprise series

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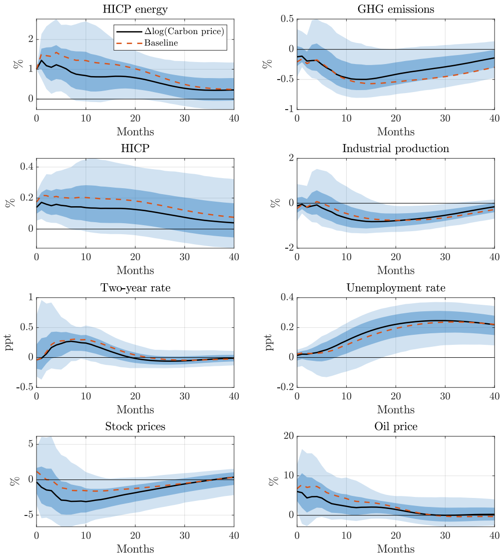
Change in carbon price relative to electricity prices



First stage regression: F-statistic: 16.69, R^2: 2.51%

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External instrument approach

- Structural VAR

$$\mathrm{y}_t = \mathrm{b} + \mathrm{B}_1 \mathrm{y}_{t-1} + \cdots + \mathrm{B}_p \mathrm{y}_{t-p} + \mathrm{S}\varepsilon_t, \qquad \varepsilon_t \sim N(0, \mathbf{\Omega})$$

- **External instrument:** variable z_t *correlated* with the **shock of interest** but *not* with the **other shocks**
- **Identifying assumptions**:

$$\mathbb{E}[z_t \varepsilon_{1,t}] = \alpha \neq 0 \qquad \text{(Relevance)}$$

$$\mathbb{E}[z_t \varepsilon_{2:n,t}] = 0, \qquad \text{(Exogeneity)}$$

$$\mathrm{u}_t = \mathrm{S}\varepsilon_t \qquad \text{(Invertibility)}$$

- Use **carbon policy surprise series** as *external instrument* for **energy price**

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Internal instrument approach

- Augment VAR by external instrument: $\bar{y}_t = (z_t,\ y_t')'$

$$\bar{y}_t = b + B_1\bar{y}_{t-1} + \cdots + B_p\bar{y}_{t-p} + S\varepsilon_t, \qquad \varepsilon_t \sim N(0, \boldsymbol{\Omega})$$

- **Identifying assumptions**:

$$\mathbb{E}[z_t\varepsilon_{1,t}] = \alpha \neq 0 \qquad \text{(Relevance)}$$

$$\mathbb{E}[z_t\varepsilon_{2:n,t}] = 0, \qquad \text{(Contemporaneous exogeneity)}$$

$$\mathbb{E}[z_t\varepsilon_{t+j}] = 0, \quad \text{for } j \neq 0 \qquad \text{(Lead-lag exogeneity)}$$

- Robust to **non-invertibility** but instrument has to be orthogonal to leads and lags of structural shocks

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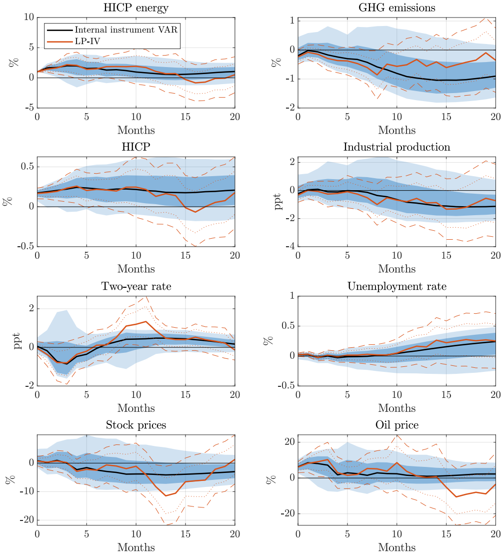
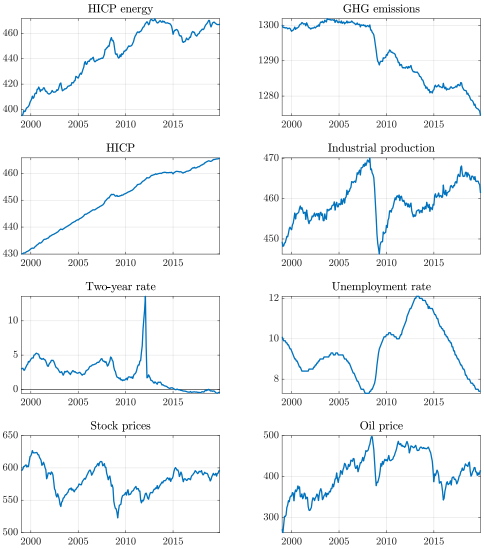
Local projections versus internal instrument approach

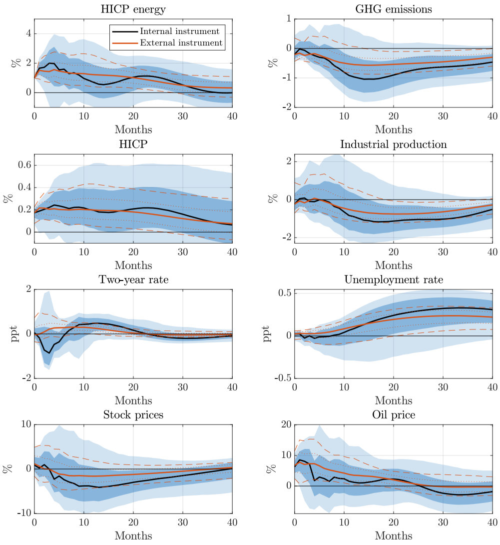


Data


HICP energy
460
440
420
400
2000
2005
2010
2015
GHG emissions
1300
1290
1280
2000
2005
2010
2015
HICP
460
450
440
430
2000
2005
2010
2015
Industrial production
470
460
450
2000
2005
2010
2015
Two-year rate
10
5
0
2000
2005
2010
2015
Unemployment rate
12
10
8
2000
2005
2010
2015
Stock prices
650
600
550
500
2000
2005
2010
2015
Oil price
500
400
300
2000
2005
2010
2015

Back

Internal versus external instrument approach



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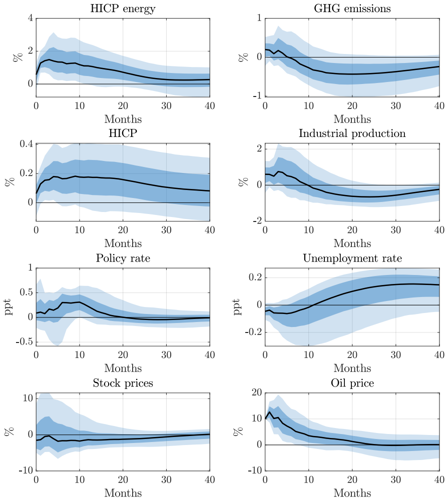
Responses to oil supply news shock



First stage regression: F-statistic: 5.74, R^2: 2.85%

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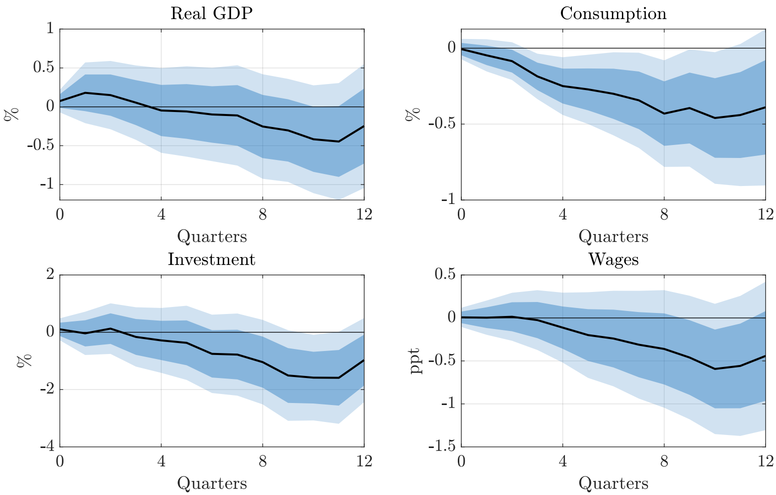
Responses to oil supply news shock



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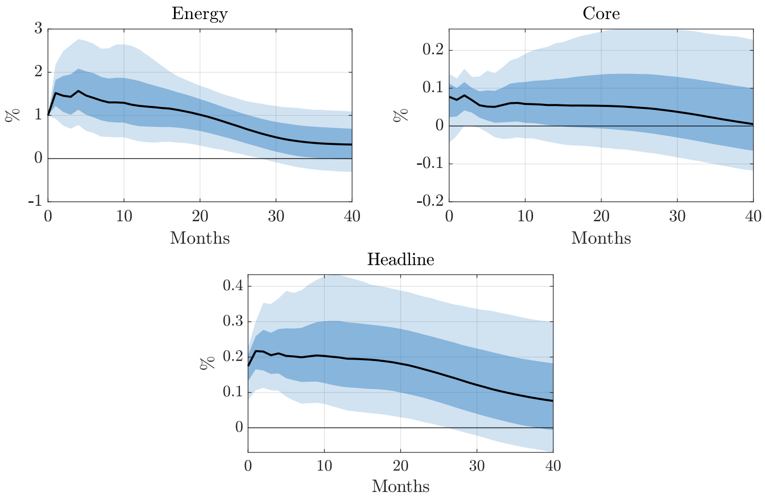
Consumer price responses



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Historical importance

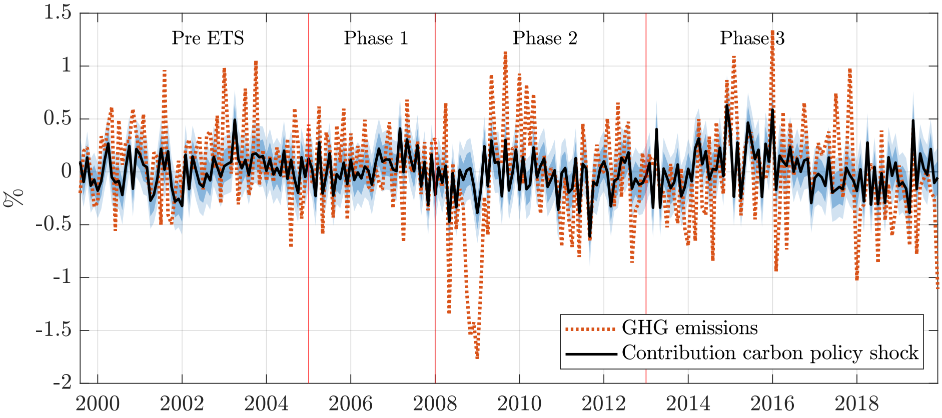

Figure 11: Historical decomposition of emissions growth

Historical importance

- **Carbon policy shocks** have **contributed meaningfully** to historical variations in energy prices, emissions and macro variables
- **But**: Did **not** account for the fall in emissions following the global financial crisis
  - supports the **validity** of the identified shock

▸ More ◂ Back

Historical importance

Table 4: 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]

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Descriptive statistics

Table 5: Descriptive statistics on households in the LCFS

	Overall	By income group		
		Low-income	Middle-income	High-income
Income and expenditure				
Normal disposable income	6,748	3,740	6,807	10,866
Total expenditure	4,458	3,025	4,444	6,238
Energy share	7.2	9.5	7.2	5.2
Non-durables (excl. energy) share	81.5	81.6	81.6	81.3
Durables share	11.2	8.9	11.2	13.5
Household characteristics				
Age	51	47	54	49
Education (share with post-comp.)	34.0	25.7	29.7	51.2
Housing tenure				
Social renters	20.8	46.9	17.4	3.7
Mortgagors	42.3	25.5	41.3	60.0
Outright owners	36.9	27.7	41.3	36.4

Descriptive statistics

Table 5: Descriptive statistics on households in the LCFS

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Mortgagors	42.3	25.5	41.3	60.0
Outright owners	36.9	27.7	41.3	36.4

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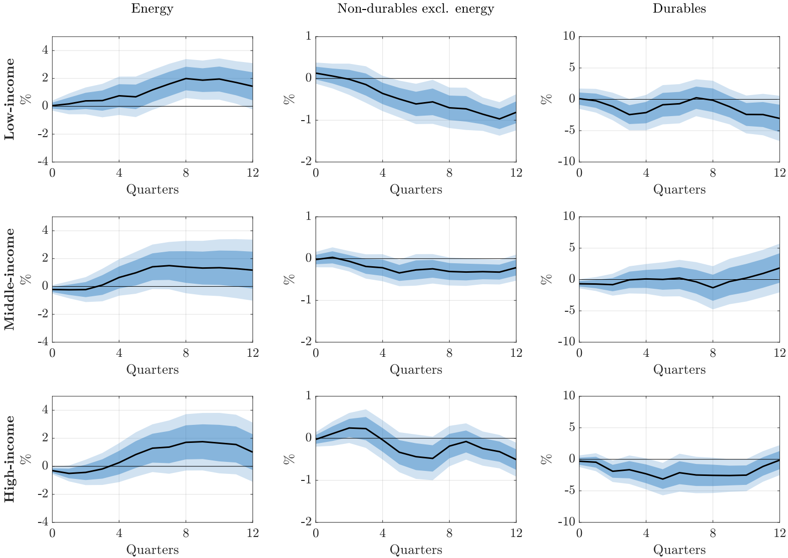
Energy versus non-energy expenditure



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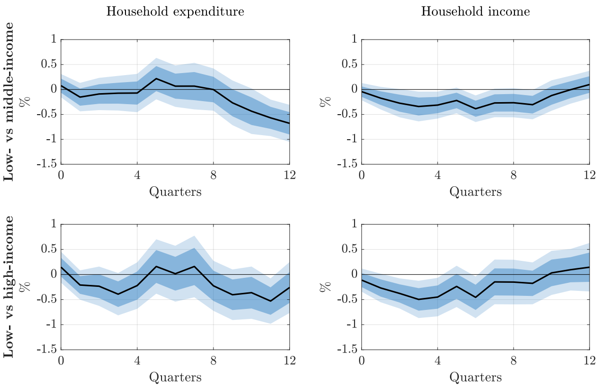
Group differences



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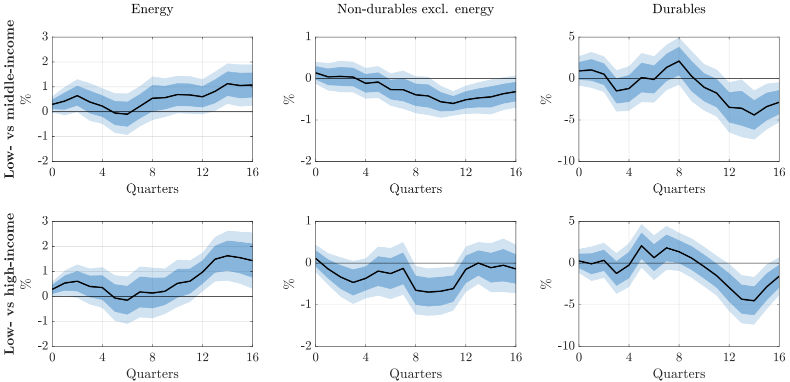
Group differences



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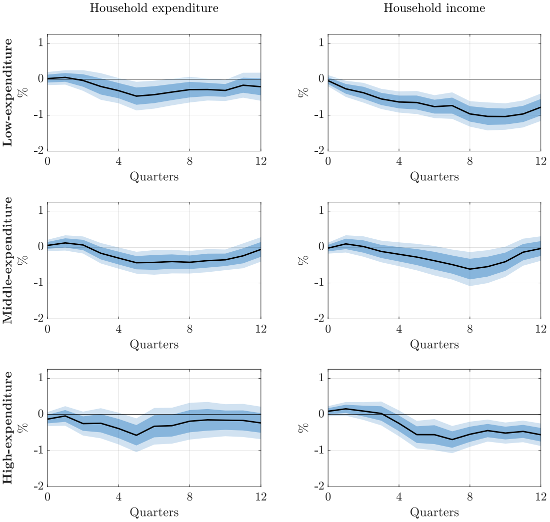
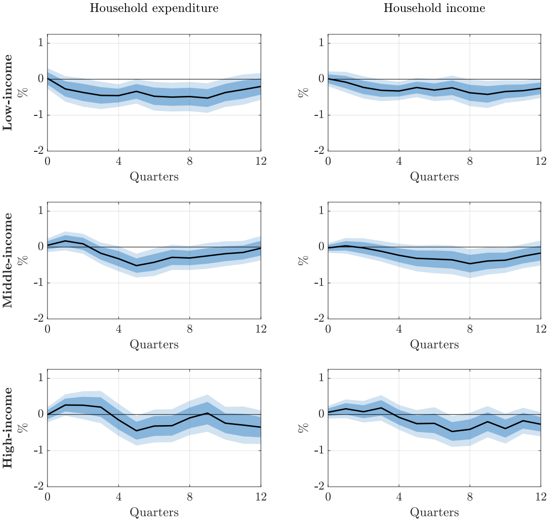
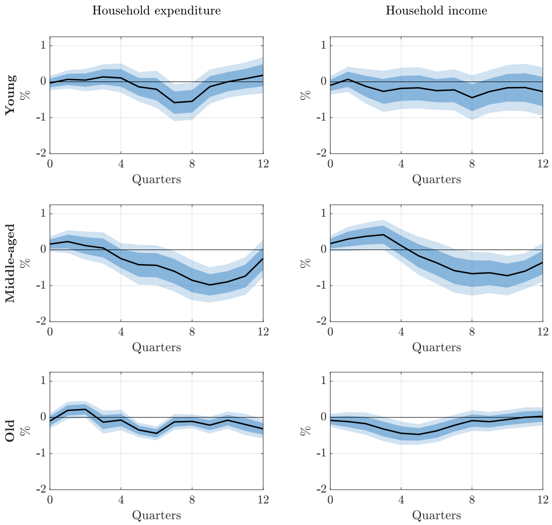
Group by expenditure



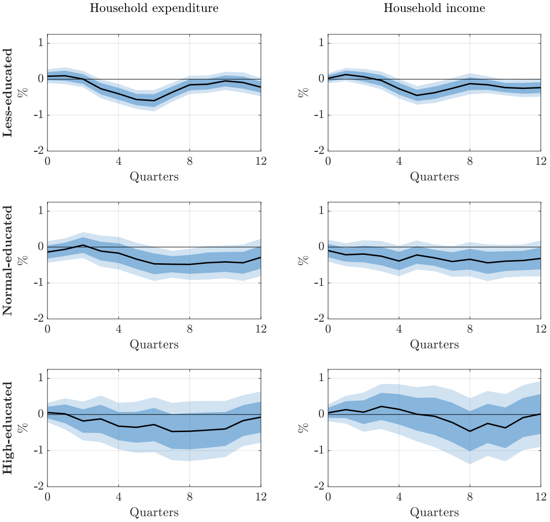
Group by permanent income



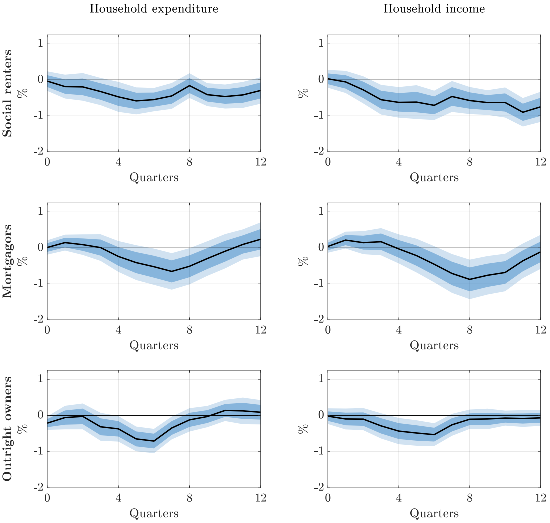
Group by age


Household expenditure
Household income
Young
Middle-aged
Old
%
1
0
-1
-2
0
4
8
12
Quarters

Group by education



Group by housing tenure



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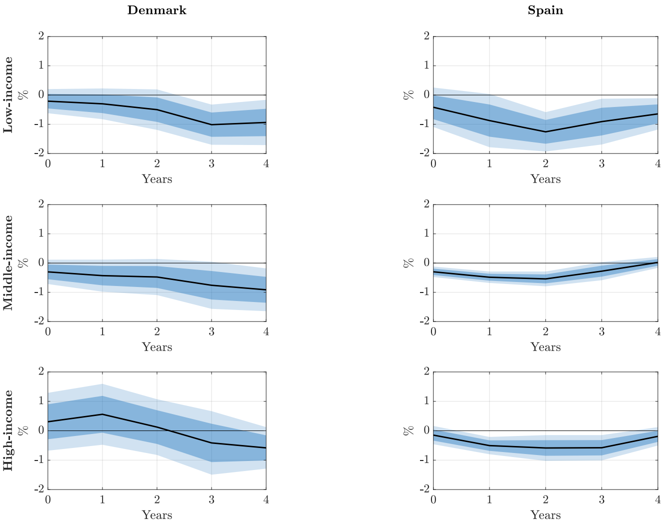
External validity



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Heterogeneity by sector of employment

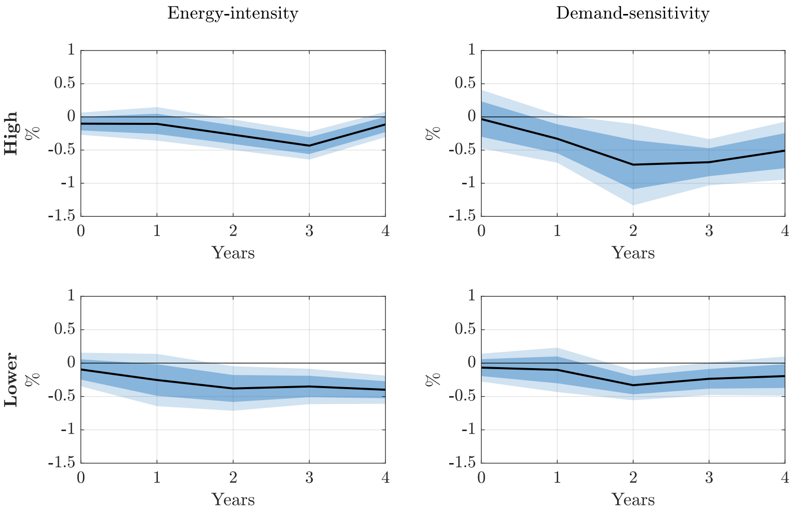

Figure 12: Income response by sector of employment

Heterogeneity by sector of employment

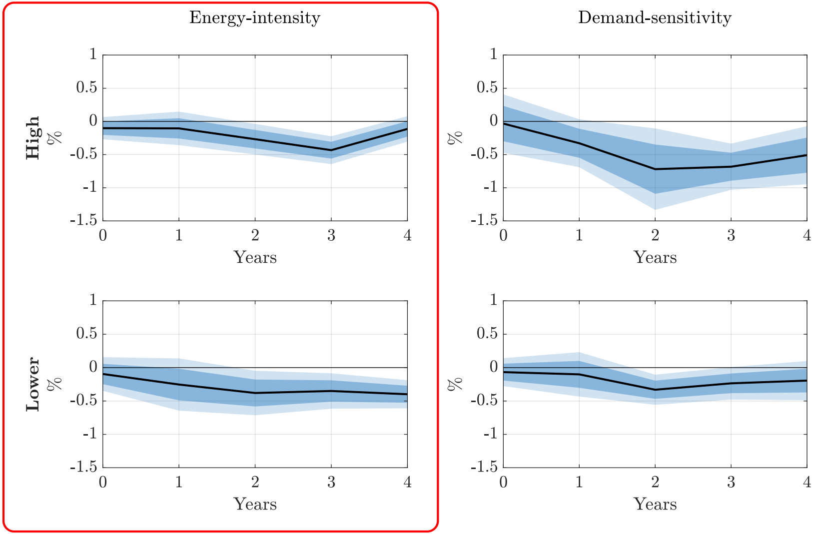

Figure 12: Income response by sector of employment

Heterogeneity by sector of employment

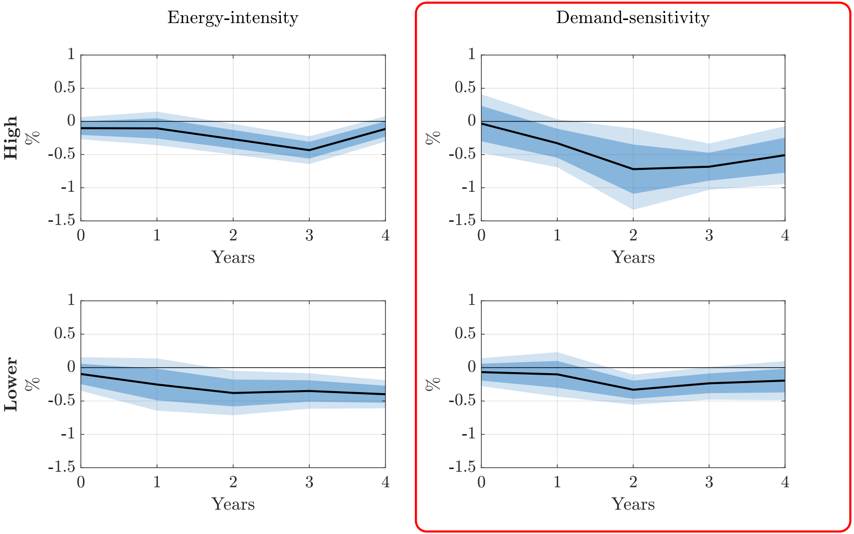

Figure 12: Income response by sector of employment

Heterogeneity by sector of employment

Table 6: Sectoral distribution of employment

Sectors	Overall	By income group		
		Low-income	Middle-income	High-income
Energy-intensity				
High	21.6	9.8	25.6	25.8
Lower	78.4	90.2	74.4	74.2
Demand-sensitivity				
High	30.5	49.0	27.2	18.1
Lower	69.5	51.0	72.8	81.9

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Heterogeneity by sector of employment

Table 6: Sectoral distribution of employment

Sectors	Overall	By income group		
		Low-income	Middle-income	High-income
Energy-intensity				
High	21.6	9.8	25.6	25.8
Lower	78.4	90.2	74.4	74.2
Demand-sensitivity				
High	30.5	49.0	27.2	18.1
Lower	69.5	51.0	72.8	81.9

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Definition of sector groups

Table 7: Sectors by energy intensity and demand sensitivity

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

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Definition of sector groups

Table 8: Sector classification

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

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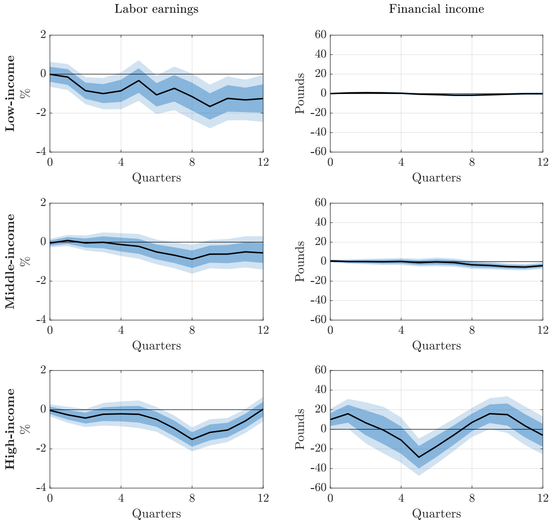
Earnings and financial income



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Energy expenditure

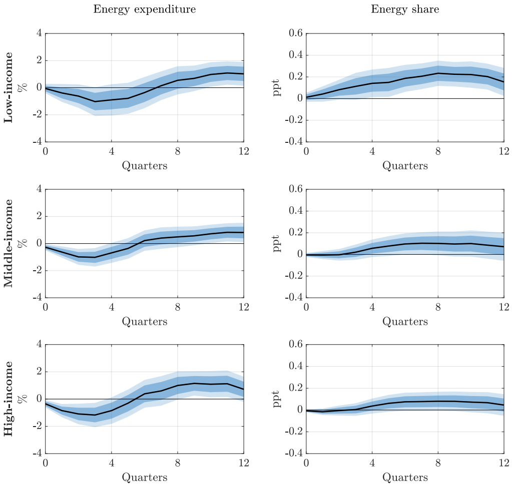

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Figure 13: Energy expenditure and energy share by income group

Redistributing carbon revenues

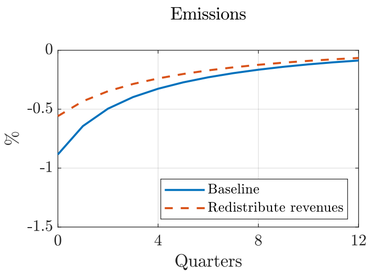

Figure 14: Responses to carbon tax shock

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Model details

Households

- Two types of households: λ hand-to-mouth H and $1-\lambda$ savers S
- Hand-to-mouth live paycheck to paycheck, consume all their income
- Savers choose consumption intertemporally, save/invest in capital and bonds
- Households subject to idiosyncratic risk: switch between types
  - probability to stay saver s, probability to stay hand-to-mouth h
- Only risk-free bonds are liquid and can be used to self-insure
- Centralized labor market structure: union sets wages

$$w_t = \varphi h_t^{\theta} \left(\lambda \frac{1}{p_{H,t}} U_x(x_{H,t}, h_t) + (1-\lambda) \frac{1}{p_{S,t}} U_x(x_{S,t}, h_t) \right)^{-1}$$

Model details

- Savers maximize lifetime utility $\mathbb{E}_0 \left[\sum_{t=0}^{\infty} \beta^t U(x_{S,t}, h_t)\right]$ subject to budget constraint and capital accumulation
- Consumption good is composite of energy and non-energy good
$$x_{S,t} = \left(a_{S,c}^{\frac{1}{\epsilon_X}} c_{S,t}^{\frac{\epsilon_X - 1}{\epsilon_X}} + a_{S,e}^{\frac{1}{\epsilon_X}} e_{S,t}^{\frac{\epsilon_X - 1}{\epsilon_X}} \right)^{\frac{\epsilon_X}{\epsilon_X - 1}}$$
- Optimizing behavior

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

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

$$\lambda_{S,t} = \beta \, \mathbb{E}_t \left[(1 + (1 - \tau^k) r_{t+1} - \delta) \lambda_{S,t+1} \right]$$

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

Model details

- Hand-to-mouth are constrained, just exhaust their budget in every period

$$
\begin{aligned}
c_{H,t} &= a_{H,c} \left(\frac{1}{p_{S,t}} \right)^{-\epsilon_x} x_{H,t} \\
e_{H,t} &= a_{H,e} \left(\frac{p_{e,t}}{p_{S,t}} \right)^{-\epsilon_x} x_{H,t} \\
p_{H,t} x_{H,t} &= y_{H,t}
\end{aligned}
$$

Model details

Firms

- Energy producers, subject to carbon tax τ_t

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

- Consumption good producers

$$y_t = e^{-\gamma s_t} \left[(1-\nu)^{\frac{1}{\epsilon_y}} \left(a_t k_t^{\alpha} h_{y,t}^{1-\alpha} \right)^{\frac{\epsilon_y - 1}{\epsilon_y}} + \nu^{\frac{1}{\epsilon_y}} \left(e_{y,t} \right)^{\frac{\epsilon_y - 1}{\epsilon_y}} \right]^{\frac{\epsilon_y}{\epsilon_y - 1}}$$
$$r_t = \alpha v_{1,t} mc_t \frac{y_t}{k_t}$$
$$w_t = (1-\alpha) v_{1,t} mc_t \frac{y_t}{h_{y,t}}$$
$$p_{e,t} = v_{2,t} mc_t \frac{y_t}{e_{y,t}}$$
$$\hat{\pi}_t = \kappa \hat{mc}_t + \beta E_t \hat{\pi}_{t+1}$$

Model details

Climate block

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

Fiscal and monetary policy

$$\begin{aligned}
\lambda\omega_{H,t} &= \tau^d d_t + \tau^k r_t^K k_t + \mu\tau_t p_{e,t} e_t \\
(1-\lambda)\omega_{S,t} &= (1-\mu)\tau_t p_{e,t} e_t \\
\tau_t &= (1-\rho_\tau)\tau + \rho_\tau \tau_{t-1} + \epsilon_{\tau,t} \\
\hat{r}_t^b &= \rho_r \hat{r}_{t-1}^b + (1-\rho_r)(\phi_\pi \hat{\pi}_{T,t} + \phi_y \hat{y}_t) + \epsilon_{mp,t}
\end{aligned}$$

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Calibration

Parameter	Description	Value	Target/Source
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	Smets and Wouters (2003)
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%; Christopoulou and Vermeulen (2012)
θ_p	Calvo parameter	0.825	Average price duration of 5-6 quarters; Alvarez et al. (2006)
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	Smets and Wouters (2003)
ρ_r	Interest smoothing	0.8	Smets and Wouters (2003)
τ	Steady-state carbon tax	0.039	Implied tax rate from average EUA price
ρ_τ	Persistence carbon tax shock	0.85	Mean-reversion of approx. 20 quarters

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Role of heterogeneity

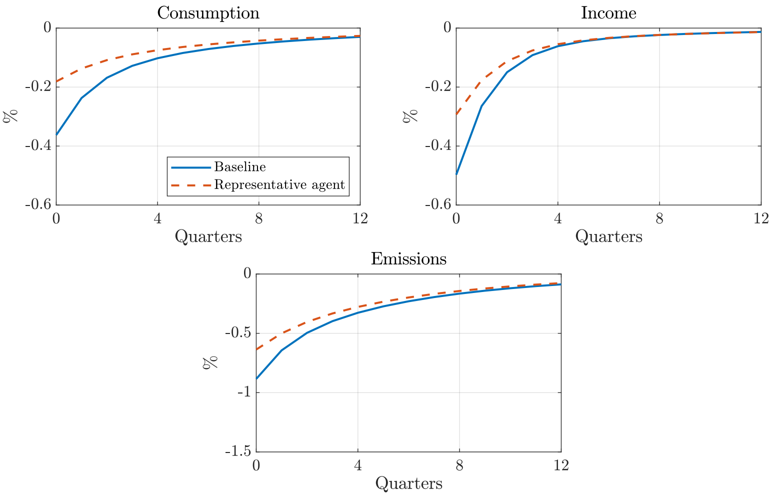

Figure 15: Responses to carbon tax shock

Role of monetary policy

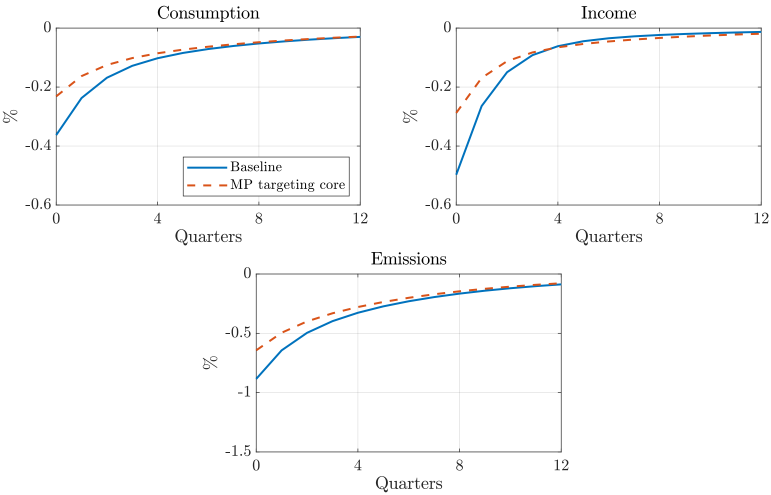

Figure 16: Responses to carbon tax shock

Attitudes towards climate policy

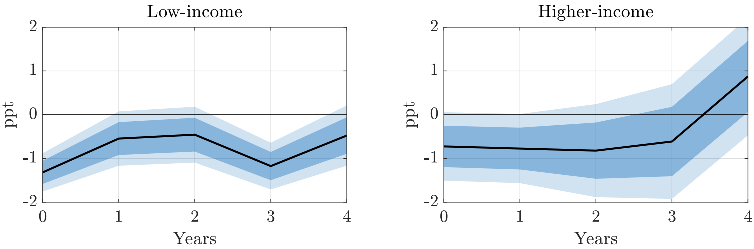

Figure 17: Effect on attitude towards climate policy by income group

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No effect on innovation for oil shocks

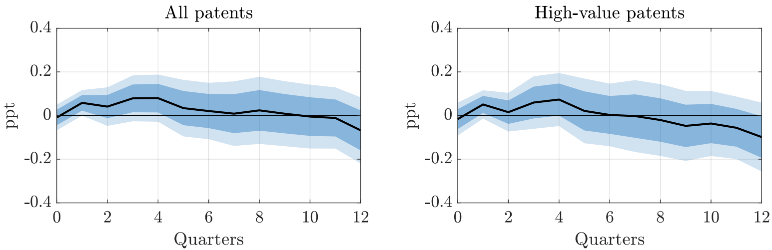

Figure 18: Share of low-carbon patents

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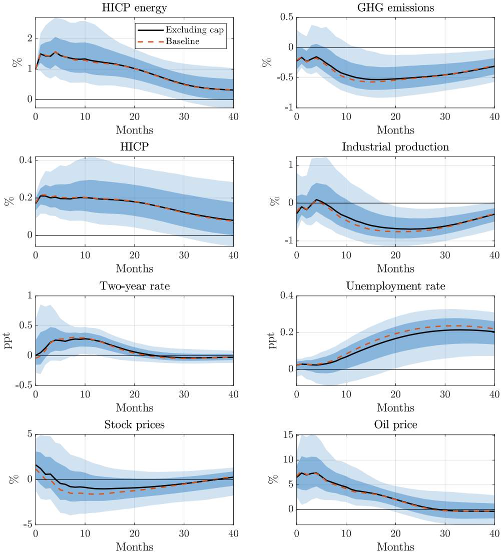
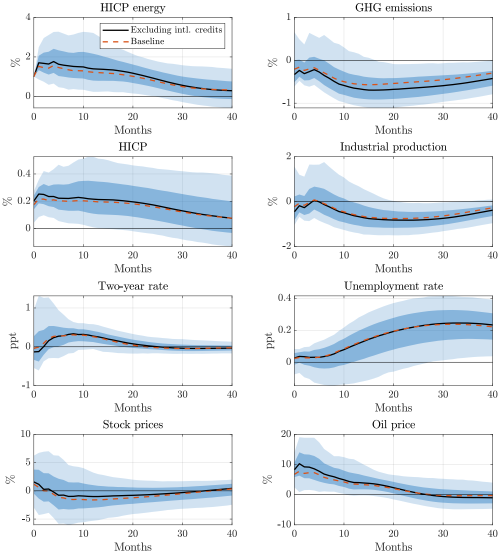
Excluding events regarding cap



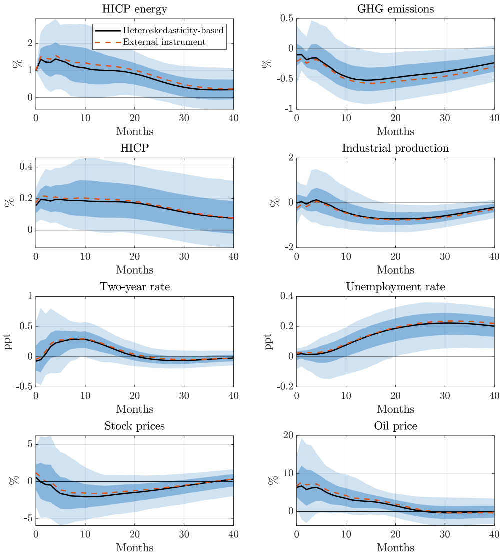
First stage regression: F-statistic: 18.97, R^2: 3.09%

Excluding events regarding international credits

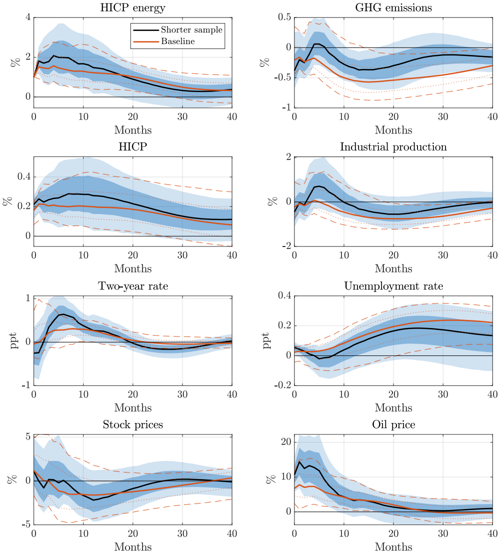


First stage regression: F-statistic: 11.99, R^2: 1.79%

Heteroskedasticity-based identification

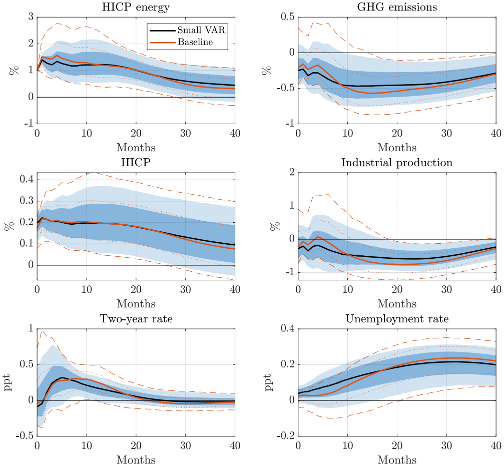


2005-2018 sample



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

Responses from smaller VAR



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

VARs with different lag orders