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Brendan Berthold, [1] Ambrogio Cesa-Bianchi,[2] Federico Di Pace [3] and Alex Haberis[4]

Abstract

This paper investigates the economic effects of carbon pricing policies using a panel of countries that are members of the EU Emissions Trading System. Carbon pricing shocks lead, on average across countries, to a decline in economic activity, higher inflation, and tighter financial conditions. These average responses mask a large degree of heterogeneity: the effects are larger for higher carbon-emitting countries. To sharpen identification, we exploit granular firm-level data and document that firms with higher carbon emissions are the most responsive to carbon pricing shocks. We develop a theoretical model with green and brown firms that accounts for these empirical patterns and sheds light on the transmission mechanisms at play.

Key words: Business cycles, carbon pricing shocks, heterogeneity, asset prices.

JEL classification: E32, E50, E60, H23, Q54.

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(1) University of Lausanne. Email: brendan.berthold@gmail.com
(2) Bank of England. Email: ambrogio.cesa-bianchi@bankofengland.co.uk
(3) Bank of England. Email: federico.dipace@bankofengland.co.uk
(4) Bank of England. Email: alex.haberis@bankofengland.co.uk

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Bank of England, Threadneedle Street, London, EC2R 8AH
Email: enquiries@bankofengland.co.uk

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1 Introduction

In order to achieve the objectives of the Paris Agreement, governments around the world need to increase the ambition and implementation of climate change mitigation policies.[1] Cap-and-trade schemes, which set overall limits on the quantities of emissions of greenhouse gases (GHGs) and allow their price to be determined by market forces, are likely to (continue to) be an important part of the climate policy mix necessary to meet objectives on climate change mitigation. The European Union Emissions Trading System (EU ETS), introduced in 2005 under the Kyoto Protocol, is one such scheme and has reduced emissions in relevant sectors in the EU by over 40 percent. Moreover, in July 2021 the European Commission announced that the emissions limits defined by the ETS would be made stricter in order to reduce GHG emissions in the EU by at least 55 percent relative to 1990 levels by 2030. While cap-and-trade schemes have long been part of the economic analysis of pollution mitigation, evidence on their wider economic and macroeconomic effects remains relatively limited.

The aim of this paper is, therefore, to provide empirical evidence on the economic effects of carbon pricing shocks and to delve into their transmission mechanism. Our key innovation is to document the heterogeneous effects of carbon policies on macroeconomic and firm-level outcomes based on CO_2 intensity, and to exploit such heterogeneity to learn about the propagation of the shock to the economy. This analysis is an important step towards understanding the macroeconomic and microeconomic implications of policies that governments would need to implement during the transition to a low-carbon economy.

Our analysis consists of three steps. First, we document the macroeconomic effects of carbon pricing shocks for a panel of 15 euro area countries. We define carbon pricing shocks as exogenous variations of the carbon futures prices in the EU ETS following Känzig (2023). We use the resulting carbon policy surprise (CPS) series in a panel local projection, and show that carbon pricing shocks are contractionary, inflationary, and lead to a significant tightening of financial conditions. A one standard deviation carbon pricing shock leads to a contraction in real GDP of about 0.2 percent and an increase in consumer prices of about 0.05 percent. The shock also triggers a fall in equity prices of more than 2 percent, and an increase in credit spreads of about 10 basis points. The cross-country dimension of our

[1] For example, see the 2022 G7 Leaders' Communiqué.

analysis allows us to investigate whether carbon pricing shocks have heterogeneous effects depending on a country's CO_2 emissions intensity. The results suggest that countries with higher CO_2 intensity tend to suffer relatively more from carbon pricing shocks, with larger falls in output and equity prices, and larger increases in credit spreads and inflation.

Second, we exploit granular firm-level data to sharpen the identification of the role of CO_2 emissions intensity for the transmission of carbon pricing shocks. In particular, we use the CPS series in a firm-level panel local projection to investigate the differential response of equity prices of high-emissions firms. The results suggest that firms with relatively higher CO_2 emissions within a sector tend to suffer significantly more than their greener counterparts. This differential effect is quantitatively significant and persistent: following a one-standard deviation carbon pricing shock, browner firms see their equity prices decrease by around 1 percent more than green firms 15 months after the initial shock.

Third, and finally, we develop a two-good model with an environmental externality and climate policies to shed light on the transmission mechanism of carbon pricing shocks. We extend the production technology proposed by Copeland and Taylor (2004) and Shapiro and Walker (2018) to allow for physical capital and embed this technology into a DSGE model. In such a setting, brown producers—those that use emissions as an input—can optimally choose to abate part of their production to limit emissions, depending on their price. The price of emissions is subject to shocks, comparable to those we employ in our empirical analysis. The model's climate block is similar to that in the DICE model proposed by Nordhaus (2008), and adopted by Heutel (2012) and Annicchiarico and Di Dio (2015), among others, in that firm emissions increase the level of atmospheric carbon, causing damages which harm aggregate productivity. Nominal and real rigidities are embedded in order to assess the impact of carbon pricing shocks on aggregate activity, inflation and asset prices at the business cycle frequency.

In line with our empirical evidence, in the model, positive carbon pricing shocks are recessionary, inflationary, and reduce asset valuations. For brown firms, the increase in the price of carbon emissions represents, in effect, an increase in input costs, leading them to reduce output and raise goods prices. The fall in brown output drives the contraction in aggregate activity. The rise in green output, with consumers shifting their demand to the now relatively cheaper green goods, turns out to be an insufficient counteracting force.

Brown goods inflation contributes largely to the rise in aggregate inflation. There is a very small pickup in green goods inflation, reflecting the increase in demand for green goods.

Equity prices for both brown and green firms decline, consistent with a drop in current and expected profits, leading to a contraction in aggregate asset valuations. In agreement with the firm-level empirical results, brown asset prices react by more than their green counterparts. The response of brown firms' valuations is driven primarily by the rise in costs resulting from a higher price of emissions. Firms cannot easily substitute towards other inputs without incurring further costs (in terms of adjustment costs or through bidding up factor prices). The fall in green firms' asset valuations reflects the squeeze on their profits (in real terms), which results primarily from the drop in the relative price of green goods and the fact that investment is costly to adjust.

We also use the model as a laboratory to align its predictions with the empirical findings on the differential effects across countries. We therefore re-calibrate the model to match the carbon intensities of the countries in our sample and show that browner countries respond more sharply to carbon pricing shocks; in particular, we show that output, policy rates, inflation and asset prices react more strongly in model economies with higher CO_2 intensity.

Related literature Our paper contributes to a recent but growing literature on the macroeconomic implications of climate change mitigation policies. Känzig's (2023) study of surprises in the EU ETS market similarly finds that positive carbon pricing shocks lead to a rise in consumer price inflation, a fall in aggregate economic activity, and a drop in the stock market. Using data on 25 OECD countries, Moessner (2022) investigates the effect of carbon pricing shocks on inflation. He finds an important pass through to energy prices but a more limited effect on core inflation. Konradt and di Mauro (2021) document that carbon taxes have only a limited effect on inflation, and may even be deflationary. Metcalf (2019) provide evidence that carbon taxes are effective at reducing GHG emissions in Europe and British Columbia. Metcalf and Stock (2020) measure the macroeconomic impact of carbon taxes on output and employment, and find quantitatively limited effects. Using a VAR framework, Bernard et al. (2018) come to the same conclusions in British Columbia. Ciccarelli and Marotta (2021) use a panel of 24 OECD countries to investigate the macroeconomic effect of climate change, environmental policies as well as environment-related technologies. They find that the effect of climate change and climate policies is significant but quantitatively limited. Mangiante (2023) documents the heterogeneous effects of carbon pricing policies across European regions. Känzig and Konradt (2023) study the differential effects of carbon pricing and carbon taxes in a unified empirical framework, and find that the former have more severe macroeconomic consequences.

By looking at firm-level equity price responses and focusing on the financial channel of climate policies, our paper is also connected to the rapidly growing climate finance literature (see Giglio et al., 2021, for a survey). Investigating the cross-section of over 14,400 firms in 77 countries, Bolton and Kacperczyk (2021) document the existence of a wide-spread carbon premium, whereby firms with higher exposure to transition risk tend to have higher expected returns. Hsu et al. (2022) show that high polluting firms have smaller average returns, and link this to uncertainty about environmental policy. Choi et al. (2020) find that stock prices of carbon intensive firms tend to under-perform the market when the weather is abnormally warm. Barnett (2020) uses an event-study framework and finds that increases in the likelihood of future climate policy action leads to decline in the stock prices of firms with larger exposure to climate policy risk. In the options markets, Ilhan et al. (2021) show that the cost of protection against extreme climate risks is larger for firms with more carbon-intensive business models. Using data on more than $2,000$ publicly listed European firms, Hengge et al. (2023) show that carbon pricing shocks lead to negative abnormal stock returns which increase with a firm's carbon intensity.

We also contribute to the literature incorporating the carbon cycle and climate policies into workhorse macroeconomic models. This literature typically examines the influence on business cycle dynamics of alternative climate policy regimes, particularly cap-and-trade schemes and carbon taxes, in response to productivity (or other economic) shocks (see Annicchiarico et al., 2022, for a survey). In doing so, it seeks to shed light on differences in climate policy regimes from positive and normative perspectives. From a positive standpoint, cap-and-trade policies tend to deliver lower output volatility than a carbon tax (for example, Fischer and Springborn, 2011). From a normative perspective, Heutel (2012) shows that the Ramsey-optimal emissions cap and carbon tax are both pro-cyclical (i.e. so that the cap-and-trade scheme is more stringent in expansions, while the carbon tax is more stringent in recessions, and vice versa). In addition, Angelopoulos et al. (2013) find that optimal environmental tax is pro-cyclical after an economic shock, and countercyclical after environmental shocks. As such, the focus of this literature differs from the approach that we take, which is instead to shed light on the transmission mechanism of climate policy by considering the impact of exogenous changes in the policy itself.

The paper is structured as follows. Section 2 describes the data sources. Section 3 reports the results from the panel country-level local projection exercise. Section 4 reports the results from the panel firm-level local projection exercise. Section 5 rationalizes our empirical findings with a theoretical model with a climate block and brown and greens firms. Section 6 concludes.

2 Data

We compile our data set by combining several sources: settlement prices of the European Union Allowance carbon futures contracts around a selected list of regulatory events that affected the supply of emission allowances (as in Känzig, 2023) from Datastream; macroeconomic and financial data from National Statistical Offices and corporate bond spreads data from ICE BoAML for a panel of countries that are member of the EU ETS carbon market; and firm-level data on equity prices and CO_2 emissions for all the firms included in the major equity indices of each country in our sample from Datastream. Below, we briefly describe each data source, while additional details and summary statistics of the data are provided in Appendix A.

Identification of Carbon Pricing Shocks A key challenge in measuring carbon pricing shocks is that most of the variation in carbon prices is driven by their endogenous response to aggregate economic conditions. To address this challenge, we rely on the approach developed by Känzig (2023), which exploits high-frequency variation in futures prices in the EU ETS carbon market around a selected list of regulatory events that affected the supply of emission allowances.[2]

Specifically, we compute a set of carbon policy surprises (CPS) as the price variation of the European Union Allowance (EUA) futures prices around 113 regulatory events about the supply allowances of carbon emissions within the EU. As in Känzig (2023), we compute

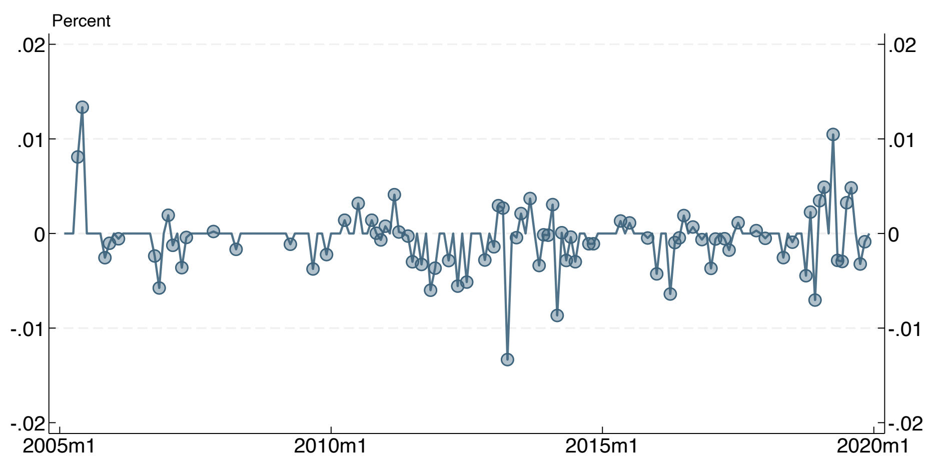
[2]The EU ETS market is a perfect laboratory for our empirical exercise. It is the largest carbon market in the world, covering roughly 40 percent of the EU greenhouse gases emissions.

the surprises as the price change in carbon prices relative to the prevailing wholesale electricity price on the day before the event—so as to avoid large fluctuations due to the fact that carbon prices were close to zero towards the end of the first phase of the EU ETS. More formally, letting $F_{t,d}$ be the (log) settlement price of the EUA futures contract in month t on day d and $P^{elec}_{t,d}$ the wholesale electricity price in month t on day d, we compute:

$$CPS_{t,d} = \frac{F_{t,d} - F_{t,d-1}}{P^{elec}_{t,d-1}}. \tag{1}$$

As the EUA futures market is liquid, futures prices are likely to incorporate all relevant information available to investors. Thus, the identified surprise in carbon futures prices captures the unexpected component of the information released in the regulatory event. Of course, it is crucial that the events do not coincide with other economic announcements, such as the demand of emission allowances or variations in economic activity in the EU. To address these concerns, Känzig (2023) selects only regulatory events that were specifically about changes in the supply of emission allowances in the European carbon market, and does not include broader events such as outcomes of Conference of the Parties (COP) meetings or other international conferences.

Figure 1 The Carbon Policy Surprises Series



Note. Replication of the high frequency carbon policy surprises of Känzig (2023). The CPS series is constructed by dividing the daily change in the settlement price of the EUA futures contract around each event by the wholesale energy price, and summing over the daily surprises in a given month. In months without any regulatory events, the series takes zero value.

As is common in the high-frequency identification literature, we then aggregate the daily series to the monthly frequency by taking the sum of the daily surprises within a given month. In months without events, the series takes the value of zero. Figure 1 shows the resulting series of carbon policy surprises. As shown in Känzig (2023), the series is not serially correlated, is not Granger caused by other variables, and is not significantly correlated with other measures of structural shocks from the literature (including oil, uncertainty, financial, fiscal and monetary policy shocks).

Country-level ('Macro') Data We collect macroeconomic and financial data at the monthly frequency for a panel of 15 advanced economies that are members of the EU Carbon ETS, namely Austria, Belgium, Denmark, Finland, France, Germany, Greece, Italy, Ireland, the Netherlands, Norway, Portugal, Spain, Sweden, and the United Kingdom.[3] Specifically, for each country, we collect data from Datastream on (a monthly measure of) real GDP;[4] the Harmonised Index of Consumer Prices (HICP), as well as its energy component; the yield on two-year government bonds, as a proxy for monetary policy (given that, for a large part of our sample, many economies were at the zero lower bound); and an index of equity prices. We also collect data on a country-specific measure of (option and maturity adjusted) corporate bond spreads from ICE Bank of America Merrill Lynch. We complement this set of macroeconomic and financial variables at the country level with Gilchrist and Zakrajšek (2012)'s Excess Bond Premium (EBP). The real GDP series and price indices are in log-levels, the short-term rate expressed in percentage points, and the corporate bond spreads and EBP are expressed in basis points.

Firm-level ('Micro') Data We collect equity price data for firm j in country i at monthly frequency for the constituents of the main equity indices of the countries in our sample. We complement the equity price data with firm-level proxies for 'carbon intensity', which we denote by $CO2_{ij,t}$. Specifically, we consider both Scope 1 and Scope 2 CO_2 emissions at the firm level from Datastream, which are available at the annual frequency. Scope 1 emissions include greenhouse gases (GHG) emissions that emanate from the operation

[3] As discussed below, the choice of countries is dictated by the availability of data on firm-level CO_2 emissions.

[4] The monthly GDP measure is obtained by interpolating quarterly level data using a shape-preserving piecewise cubic interpolation, as in Miranda-Agrippino and Rey (2020).

of capital directly owned by the firms. Scope 2 emissions are indirect emissions associated with the purchase of electricity, steam, heat, or cooling. As the two measures are complementary, we consider a measure that sums Scope 1 and Scope 2 emissions. Table B.2 in Appendix A provides summary statistics on our measures of carbon intensity by country, as well as additional information about the data coverage. Finally, we collect data on a number of firm-level controls available at the quarterly frequency from Datastream, namely a measure of leverage (measured as the ratio of total debt to assets), a measure of profitability (sales growth), and a measure of size (total assets).

Final sample Our baseline data set runs from May 2005 to December 2019, covers 113 regulatory events about the supply allowances of carbon emissions within the EU, includes country-level macroeconomic data for 15 countries, and has firm-level information on equity prices, balance sheet data, and CO_2 emissions for 521 unique firms. Our baseline sample period is restricted by the availability of the carbon policy surprises, which only start in May 2005. To avoid the large shocks associated with the Covid-19 pandemic, we stop our sample in December 2019. The choice of countries is instead dictated by the availability of firm-level CO_2 data, which we require to cover at least 70% of the available sample for each country.

3 Macro Evidence: Country-level Panel Local Projections

In this section we provide evidence on the macroeconomic effect of carbon pricing surprises using aggregate data for the countries in our data set. The panel dimension of our data set allows us to investigate both the behavior of the 'average' economy in response to the shock and the cross-country differences in its transmission. We thus proceed in two steps. First, we estimate the impact of carbon pricing shocks on macroeconomic variables and asset prices using a panel local projections model. Second, we provide evidence on the heterogeneous effects of the surprises across countries depending on their CO_2 intensity.

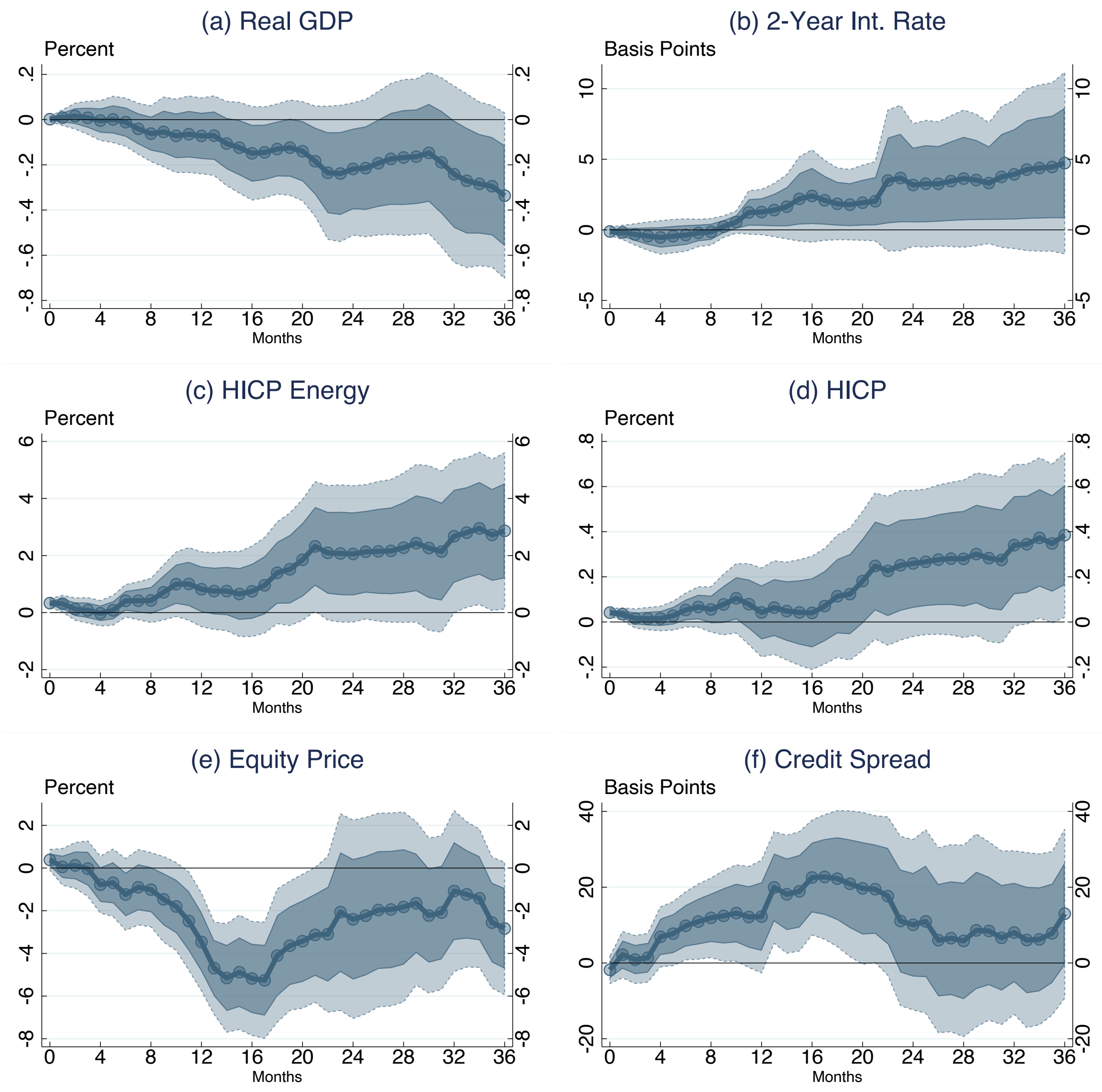
Response of the 'Average' Economy To estimate the average effects of carbon pricing shocks we employ a panel local projections approach. Letting $y_{i,t+h}$ denote a generic outcome variable for country i observed h periods from today, we consider variants of the following specification:

$$y_{i,t+h} - y_{i,t-1} = \alpha_i^h + \beta^h CPS_t + \sum_{p=1}^{P} \Gamma_p^h X_{i,t-p} + u_{i,t+h}, \tag{2}$$

where α_i^h is a country fixed effect at horizon h that captures permanent differences across countries; CPS_t is the carbon pricing shock described above; and $X_{i,t}$ collects all additional controls, including lags of the outcome variable and of the other macro aggregates in our data set (namely, log real GDP, log headline HICP, log energy HICP, a log index of equity prices, the two-year interest rate, and credit spreads), lags of the carbon pricing surprise, lags of the Excess Bond Premium of Gilchrist and Zakrajšek (2012), and a linear trend. We set the maximum number of lags to $P = 6$. Standard errors are clustered two-way, at the country-month level.

Figure 2 plots the coefficient of interest β^h, which captures the dynamic effects of a one standard deviation shock to the CPS series on macro aggregates and asset prices at horizon h for the *average country*. The impulse responses show that carbon pricing shocks resemble negative supply shocks insofar as they lead to a decrease in real GDP and an increase in consumer prices, largely driven by the increase in the energy component of HICP. Specifically, real GDP gradually decreases to around -0.3 percent below trend after 20 months, and stabilizes at that level thereafter. Consistent with the results in Känzig (2023), the energy component of the HICP increases persistently, with an impact effect of about 0.4 percent, which gradually and persistently increases over time reaching a peak of about 3 percent after 36 months. The headline HICP mirrors the behavior of the energy HICP, with an impact increase of about 0.05 percent, which slowly increases to 0.4 percent. In response to these macro developments, there is a mild tightening of the monetary policy stance, with the two-year interest rate slowly but persistently increasing by about 5 basis points after 36 months. We now turn to the financial market and asset price impact of the carbon pricing shock. As in Känzig (2023), we find that equity prices do not reposnd on impact, but then quickly fall anticipating the response of economic activity. Equity prices

Figure 2 The Effect of Carbon Pricing Shocks: Average Economy



Note. Average effect of a one standard deviation increase in the carbon pricing surprise (CPS) series on $y_{i,t+h} - y_{i,t-1}$, as captured by the coefficients β^h in equation (2). Shaded areas display 68 percent and 90 percent confidence intervals computed with heteroskedasticity and autocorrelation robust standard errors (two-way clustered, at the country-month level).

reach a trough at around -5 percent after 16 months, slightly revert back, and eventually stabilize at around -2 percent at the end of the horizon considered. Credit spreads mirror the impulse response of equity prices, peaking at around 20 basis points after 16 months, before slowly reverting back over time.

Cross-country Heterogeneity The impulse responses in Figure 2 may mask some significant differences across countries. We now investigate whether countries that are more 'carbon intensive' tend to suffer more from carbon pricing shocks. To do so, we use the CO_2 intensity measure from the World Bank. This is defined as the amount of CO_2 emissions per PPP dollars of GDP, and is available at annual frequency. CO_2 intensity is widely heterogeneous across the 15 countries in our sample. The average level of CO_2 intensity across countries is 0.28, and it ranges from 0.18 for Sweden to 0.38 for Finland.[5]

To estimate the heterogeneous effects of carbon pricing shocks depending on a country's CO_2 intensity we specify the following local projections model:

$$y_{i,t+h} - y_{i,t-1} = \alpha_i^h + \alpha_t^h + \gamma^h \left(CPS_t \times CO2_{i,t-1}\right) + \sum_{p=1}^{P} \Gamma_p^h X_{i,t-p} + u_{i,t+h}, \tag{3}$$

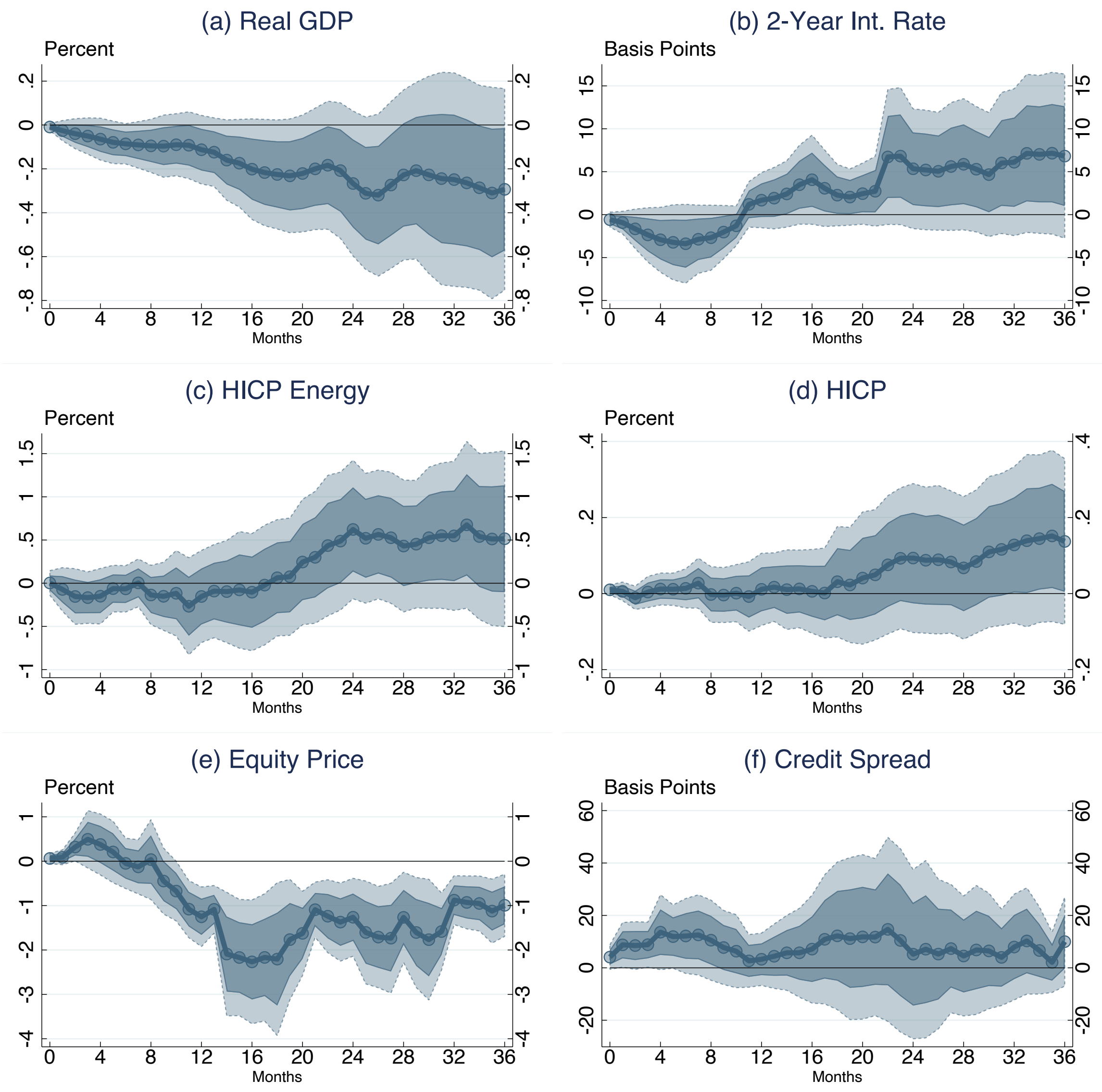
where α_i^h is a country fixed effect at horizon h; α_t^h is a time fixed effect at horizon h; CPS_t is the carbon pricing shock; $CO2_{i,t}$ is the country-level carbon intensity measure described above; and $X_{i,t}$ collects all additional controls, including lags of the outcome variable and of the other macro aggregates in our data set (namely, log real GDP, log headline HICP, log energy HICP, a log index of equity prices, the two-year interest rate, and credit spreads). To facilitate the interpretation of the estimated coefficient γ^h, we standardize the country's carbon intensity variable over the entire sample, so its units are standard deviations in our sample. Standard errors are clustered two-way, at the country-month level.

Figure 3 plots the coefficient of interest γ^h, which captures the dynamic effects of a one standard deviation shock to the CPS series on macro aggregates and asset prices (at horizon h) for a high-emission country (i.e. a country whose carbon intensity $CO2_{i,t}$ is one standard deviation above the average carbon intensity in our sample) *relative* to the average country. The impulse responses show that countries with higher CO_2 intensity tend to experience larger effects from the carbon pricing shock, namely a larger drop in output and equity prices, a larger increase in the HICP and its energy component, and a larger increase credit spreads and in the 2-year interest rate.

In sum, the patterns we document in this section are suggestive of a significant degree of heterogeneity, with 'browner countries' suffering more severe effects in response to a carbon

[5] Table B.1 in Appendix B reports, for each country, the summary statistics of the CO_2 intensity measure over the same sample period of the baseline analysis, namely 2005 to 2019.

Figure 3 THE EFFECT OF CARBON PRICING SHOCKS: HIGH-EMISSION COUNTRIES



NOTE. Effect of a one standard deviation increase in the carbon policy surprise (CPS) series on $y_{i,t+h} - y_{i,t-1}$ for a country whose levels of CO_2 are one standard deviation above the average level of CO_2 relative to the average country, as captured by the coefficients γ^h in equation (3). Shaded areas display 68 percent and 90 percent confidence intervals computed with heteroskedasticity and autocorrelation robust standard errors (two-way clustered, at the country-month level).

pricing shock than 'greener countries'. However, the granularity of our analysis—which is constrained at the country level given the focus of this section on macro aggregates—raises a number of identification challenges. For example, the CO_2 intensity variable may correlate with other country-specific characteristics that affect the strength of the transmission of carbon pricing shocks. It is therefore difficult to establish whether more CO_2-intensive economies suffer more from carbon pricing shocks. In section 4, we tackle these limitations by leveraging on granular firm-level data that allow us to sharpen substantially the identification. Before doing that, however, we report a set of additional exercises that show the robustness of the results presented in this section.

Robustness We run an extensive battery of robustness checks. First, we consider a variation of our baseline specification with a less conservative lag structure. Figures C.1 and C.2 show (for the average and relative effects, respectively) the impulse responses that we obtain using 12 lags, and compares them to our baseline. The effects of carbon pricing shocks are not affected by this choice of the lag structure.

Second, we include additional controls to our baseline specification. Figure C.3 shows the impulse responses that we obtain when we add the price of oil to the vector of controls, and compares them to our baseline. Note that, as the oil price does not vary across countries, we report only the impulse responses for the average effect—as in the 'relative effect' specification the price of oil would be absorbed by the time fixed effects. The main results are unchanged, if anything they are slightly better estimated than in our baseline. We also consider a specification that excludes the deterministic trend. Figure C.4 reports the impulse responses (for the average effect only), which are virtually identical to our baseline.

Third, we re-estimate our panel using the mean group estimator of Pesaran and Smith (1995). This is an important check, since fixed effect estimators may not be consistent in dynamic panel data with large heterogeneity in the slope coefficients across cross-sectional units (in our case, across countries). Large differences between the mean group estimator and the fixed effects estimator would reveal a potential bias. In practice, however, Figure C.5 shows that the two estimators virtually coincide (with the exception of the 2-year interest rate, for which we observe minor differences), thus generally addressing this concern.

4 Micro Evidence: Firm-level Panel Local Projections

Motivated by the suggestive cross-sectional evidence from the country-level impulse responses, this section uses a more tightly identified set up to investigate whether the effect of carbon pricing shocks varies with CO_2 intensity. In particular, we exploit granular firm-level data on equity prices and emissions to document that firms with higher CO_2 emissions experience larger drops in their equity prices following a carbon pricing shock. We focus on firms' equity prices because they provide an effective summary of firms' performance and are readily available at high frequency for many firms across many countries.

Before investigating the heterogeneous effects of carbon pricing shocks, we perform a 'sanity check' on our firm-level data by estimating the *average* effect of carbon pricing shocks on firm-level equity prices and comparing it with the average effect from the country-level analysis. To do so, we employ a panel local projections approach similar to the one used in the previous section. Letting $q_{ij,t}$ denote the log equity price of firm j in country i in period t, we consider the following regression specification:

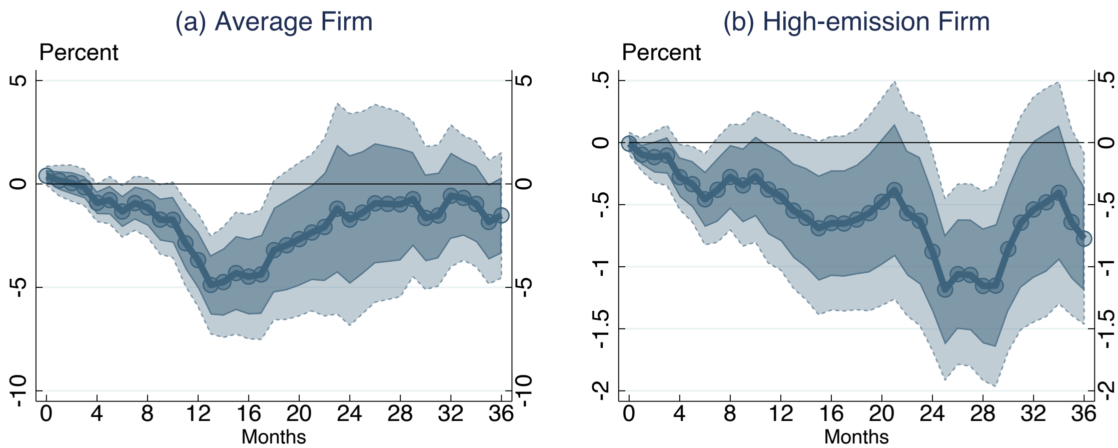
$$q_{ij,t+h} - q_{ij,t-1} = \alpha_j^h + \beta^h CPS_t + \sum_{p=1}^{P} \gamma_p^h X_{i,t} + \sum_{p=1}^{P} \Theta_p^h Z_{ij,t} + u_{ij,t+h}, \tag{4}$$

where α_j is a firm fixed-effect that captures permanent differences across firms at horizon h; CPS_t is the futures price variation in the EU ETS carbon market described in the previous section; $X_{i,t}$ is a vector of country-level controls, including lags of the macro aggregates in our data set (namely, log real GDP, log headline HICP, log energy HICP, a log index of equity prices, the two-year interest rate, and credit spreads), lags of the carbon pricing surprise, lags of the Excess Bond Premium of Gilchrist and Zakrajšek (2012), and a linear trend; $Z_{ij,t}$ is a vector of firm-level controls, including lags of the outcome variable. In line with the country level analysis, we set the maximum number of lags to $P = 6$. Standard errors are clustered two-way, at the firm-month level.

Figure 4 (panel a) plots the coefficient of interest β^h, which captures the dynamic effects (at horizon h) of a one standard deviation shock to the CPS series on equity prices for the average firm in our sample. Reassuringly, the impulse responses to the carbon pricing shocks we obtain from the firm-level data are remarkably similar to those we obtain from the country-level data. Equity prices slowly fall over time, reaching a trough at around -5 percent after 12 months, slowly revert back slightly, eventually and stabilize at around -2 percent at the end of the horizon considered.[6]

[6] To facilitate the comparison, Figure C.12 in Appendix C reports both impulse responses on the same chart.

Figure 4 The Effect of Carbon Pricing Shocks: Firm-level Equity Prices



Note. Effect of a one standard deviation increase in the carbon policy surprise (CPS) series on equity prices in the firm-level data. Panel (a) reports the equity price response of the average firm, as captured by the coefficients β^h in equation (4); panel (b) reports the equity price response of a high-emission firm (i.e. whose CO_2 emissions are one standard deviation above the average CO2 emissions) relative to the average firm, as captured by the coefficients γ^h in equation (5). Shaded areas display 68 percent and 90 percent confidence intervals computed with heteroskedasticity and autocorrelation robust standard errors (two-way clustered, at the firm-month level).

We now move on to investigate whether more carbon intensive firms tend to suffer more from carbon pricing shocks. Similarly to the previous section, we consider the following regression specification:

$$q_{ij,t+h} - q_{ij,t-1} = \alpha_j^h + \alpha_{t,i,s}^h + \gamma^h(CPS_t \times CO2_{ij,t-1}) + \sum_{p=1}^{P} \Gamma_p^h Z_{ij,t} + u_{ij,t+h}, \qquad (5)$$

where α_j is a firm fixed-effect that captures permanent differences across firms; $\alpha_{t,i,s}$ is a triple interacted fixed-effect (with time t, country i, and sector s) that controls for any sectoral time-varying factors within a country that may affect firms' equity prices; CPS_t is the futures price variation in the EU ETS carbon market described in the previous section; $Z_{ij,t}$ is a vector of firm-level controls; and $CO2_{ij,t}$ as a measure of firm-level carbon intensity. In our baseline specification, we consider the sum of Scope 1 and Scope 2 CO_2 emissions divided by a firm's total assets. In robustness analysis, we also consider a number of different definitions of the carbon intensity variable $CO2_{ij,t}$, e.g. different normalizations, as well as dummy-based definitions of high-emission firms (as opposed to the 'continuous' measure that we use in our baseline). To facilitate the interpretation of the estimated coefficient γ^h, we standardize the firm-level carbon intensity variable over the entire sample, so its units are standard deviations in our sample.

Figure 4 (panel b) plots the coefficient of interest γ^h, which captures the dynamic effects (at horizon h) of a one standard deviation shock to the CPS series on the equity price of a firm whose carbon intensity is one standard deviation above the average carbon intensity in our sample. The impulse responses show that a high-emission firm sees its equity price decrease by almost 1.5 percent more than the average-emission firm, within the same sector and country. The patterns we document in this section corroborate the results from the 'macro' evidence from the previous section, but with a substantially sharper identification of the role of heterogeneity—which is allowed by the granularity of the firm-level data. Before moving to the theoretical analysis, we report below a set of additional exercises that show the robustness of the results presented in this section.

Robustness and Additional Results We run an extensive battery of robustness checks. First, we consider different definitions of high-emission firms. Figures C.6 and C.7 show the impulse responses that we obtain when we construct the CO_2 intensity variable using Scope 1 and Scope 2 emissions, respectively (as opposed to the sum of Scope 1 and Scope 2 as in the baseline), and compares them to our baseline. The main results are unchanged, if anything the response of equity prices using Scope 2 emissions is slightly larger than the response obtained with Scope 1 emissions.

Second, we consider a different normalization for the definition of high-emission firms. Specifically, we normalize emissions by the market value of the firm instead of total assets. Figure C.8 shows that the impulse responses we obtain under this alternative measure of CO_2 intensity are unchanged.

Third, we re-estimate the baseline specification using a smaller version of the firm-level data set where we only keep the top 20 firms by market value for each country. As the equity indices of the countries we consider in the baseline analysis include a different number of firms, there is a risk that some countries may be over-represented in the firm-level data. Figure C.10 shows that the impulse responses we obtain in this exercise are almost identical to the baseline, thus addressing this concern.

Finally, we provide further evidence on the comparison between firm-level and country-level results. Specifically, we investigate whether the average firm in a high-emission country (as proxied by the country CO_2 intensity used in section 3) tends to suffer more from carbon pricing shocks than the average firms in the average country, and how such response compares to the country-level evidence. Figure C.13, which reports the results from this exercise, shows that the firm-level results are consistent with the country-level ones.

5 Making Sense of the Evidence

In this section, we rationalize the empirical results using a two-good DSGE model with climate policies. First, we outline the features of the model. We then discuss its responses to changes in climate policy in order to shed light on the mechanisms underpinning our empirical results.

5.1 Model

Our model has two types of firms—"brown" and "green"—which are distinguished by the extent to which they pollute, consistent with Copeland and Taylor (2004) and Shapiro and Walker (2018). We assume that emissions are associated with production, that firms are subject to environmental policies that make polluting costly, and that, as a result, they undertake abatement activities to limit their pollution. Whether firms are brown or green is determined by the value of one parameter, which, as described below, can be viewed as the share of emissions in production. This is assumed to be positive for brown firms and zero for green firms. This way of modelling heterogeneity is consistent with the empirical approach described in Section 4, where we estimate the differences in firm responses depending on emissions, while controlling for other factors, including time-by-sector fixed effects. The model has an endogenous carbon cycle, in which atmospheric pollution feeds back onto aggregate productivity, as well as a number of more standard real and nominal rigidities. The rest of this section outlines the model in more detail.

5.1.1 Households

Households, denoted by the index $\omega \in [0, 1]$, make consumption and investment (savings) decisions, and supply labor and capital services to producing firms. We assume that households can insure themselves against idiosyncratic changes in their wage incomes. Households hold government bonds, make investment decisions in physical capital and buy/sell stocks in mutual funds. Households maximize their life-time utility:

$$\mathcal{V}_0(\omega) = \mathbb{E}_0 \sum_{t=0}^{\infty} \beta^t \mathcal{U}\left(C_t(\omega), N_t(\omega)\right),$$

where the period utility is given by:

$$\mathcal{U}\left(C_t(\omega), N_t(\omega)\right) = \frac{\left(C_t(\omega) - \phi C_{t-1}(\omega)\right)^{1-\sigma} - 1}{1-\sigma} - \chi \frac{\left(N_t(\omega)\right)^{1+\varphi}}{1+\varphi}.$$

Here β is the subjective discount factor, $C_t(\omega)$ denotes consumption, $N_t(\omega)$ hours worked, σ is the inverse of inter-temporal elasticity of substitution, ϕ the degree of external habit formation, and φ the inverse of the Frisch elasticity of labor supply. Consumption (C_t) is a CES composite that combines consumption of goods produced by brown firms, C_t^B, with consumption of goods produced by green firms, C_t^G:

$$C_t(\omega) = \left\{\nu^{\frac{1}{\eta}} \left(C_t^B(\omega)\right)^{\frac{\eta-1}{\eta}} + (1-\nu)^{\frac{1}{\eta}} \left(C_t^G(\omega)\right)^{\frac{\eta-1}{\eta}}\right\}^{\frac{\eta}{\eta-1}}, \tag{6}$$

where η denotes the intra-temporal elasticity of substitution and ν the share of brown goods in aggregate consumption. Each household minimizes consumption expenditure by choosing C_t^B and C_t^G. The optimality conditions are given by:

$$C_t^B(\omega) = \nu \left(\frac{P_t^B}{P_t}\right)^{-\eta} C_t(\omega), \tag{7}$$

$$C_t^G(\omega) = (1-\nu) \left(\frac{P_t^G}{P_t}\right)^{-\eta} C_t(\omega), \tag{8}$$

where P_t^G, P_t^B and P_t denote the nominal prices of green, brown and aggregate goods, respectively. Substituting (7) and (8) into equation (6) gives an expression for the aggregate price index:

$$P_t = \left\{\nu \left(P_t^B\right)^{1-\eta} + (1-\nu) \left(P_t^G\right)^{1-\eta}\right\}^{\frac{1}{1-\eta}}.$$

There are investment packers, who combine investment goods produced by firms to produce an aggregate investment good. The intra-period problem of investment packers is similar to that of consumers and is detailed in the Appendix D. The evolution of capital is, however, specific to each firm type and households face costs when adjusting firm-specific investment. This means that the physical capital used by firms to produce output is a composite of brown and green goods.

The budget constraint is given by:

$$\begin{aligned} C_t(\omega) + \sum_{j=\{B,G\}} \mathcal{I}_t^j(\omega) + B_t(\omega) + \sum_{j=\{B,G\}} S_{t+1}^j(\omega) V_t^j = R_{t-1} \frac{B_{t-1}(\omega)}{\Pi_t} \\ + w_t(\omega) N_t(\omega) + \sum_{j=\{B,G\}} \left\{ r_{K,t}^j K_{t-1}^j + S_t^j(\omega) \left(V_t^j + \Phi_t^j / P_t \right) \right\} - T_t(\omega) / P_t. \end{aligned}$$

where $\mathcal{I}_t^j(\omega)$ denotes investment by firm of type $j \in \{B, G\}$, $S_t^j(\omega)$ the stock holdings in mutual fund of firm-type j, V_t^j the real price of shares of firm of type j in the mutual fund, $w_t(\omega)$ the real wage rate, $K_t^j(\omega)$ is physical capital of firms of type j, $r_{K,t}^j$ real rental rate of capital for firms of type j, $T_t(\omega)$ nominal lump-sum transfers and $\Phi_t^j(\omega)$ nominal profits. The law of motion of investment of type j is given by:

$$K_t^j(\omega) = (1-\delta_K) K_{t-1}^j(\omega) + \left(1 - \frac{\psi_j}{2} \left(\frac{\mathcal{I}_t^j(\omega)}{\mathcal{I}_{t-1}^j(\omega)} - 1 \right)^2 \right) \mathcal{I}_t^j(\omega). \tag{9}$$

Households maximize life-time utility subject to a series of budget constraints and the two laws of motion of capital. From here onwards, we drop the index ω for brevity. The first order conditions with respect to C_t, K_t^B, K_t^G, $\mathcal{I}_t^B$, $\mathcal{I}_t^G$ and B_t are given by:

$$\Lambda_t = (C_t - \phi C_{t-1})^{-\sigma} - \beta\phi \mathbb{E}_t (C_{t+1} - \phi C_t)^{-\sigma}, \tag{10}$$

$$\Lambda_t = \beta \mathbb{E}_t \left\{ \frac{R_t}{\Pi_{t+1}} \Lambda_{t+1} \right\}, \tag{11}$$

$$Q_t^j = \beta \mathbb{E}_t \frac{\Lambda_{t+1}}{\Lambda_t} \left\{ r_{K,t+1}^j + (1-\delta_K) Q_{t+1}^j \right\} \quad \text{for} \quad j = \{B, G\}, \tag{12}$$

$$\begin{aligned} 1 = & Q_t^j \left[1 - \frac{\psi_I^j}{2} \left(\frac{\mathcal{I}_t^j}{\mathcal{I}_{t-1}^j} - 1 \right)^2 - \psi_I^j \left(\frac{\mathcal{I}_t^j}{\mathcal{I}_{t-1}^j} - 1 \right) \frac{\mathcal{I}_t^j}{\mathcal{I}_{t-1}^j} \right] + \\ & + \beta \mathbb{E}_t \left\{ Q_{t+1}^j \frac{\Lambda_{t+1}}{\Lambda_t} \psi_I^j \left(\frac{\mathcal{I}_t^j}{\mathcal{I}_{t-1}^j} - 1 \right) \left(\frac{\mathcal{I}_t^j}{\mathcal{I}_{t-1}^j} \right)^2 \right\} \quad \text{for} \quad j = \{B, G\}, \end{aligned} \tag{13}$$

In addition, asset prices for j-type firms (V_t^j) can be written as:

$$V_t^j = \beta \mathbb{E}_t \frac{\Lambda_{t+1}}{\Lambda_t} \left\{ \frac{\Phi_{t+1}^j}{P_{t+1}} + V_{t+1}^j \right\}. \tag{14}$$

5.1.2 Firms

Firms are indexed by $i \in [0,1]$ and produce goods of type $j = \{B, G\}$. They face a production technology given by:

$$Y_t^j(i) = \mathcal{Z} Z_t \left(1 - A_t^j(i)\right) \left(N_t^j(i)\right)^{1-\alpha_j} \left(K_{t-1}^j(i)\right)^{\alpha_j}, \tag{15}$$

where $\mathcal{Z}$ is the level of aggregate productivity, $Z_t = 1 - \Gamma(\mathcal{CO}_t)$ denotes aggregate productivity and $\Gamma(\mathcal{CO}_t)$ is a damage function in line with Nordhaus (2008), $A_t^j(i)$ is the fraction of output devoted to abatement of pollution and α_j is the capital share in production. The damage function $\Gamma(\mathcal{CO}_t)$ captures the adverse impact of the physical damages associated with climate change on aggregate productivity. These damages represent an externality imposed by polluting firms on others. Consistent with Heutel (2012), we assume a quadratic functional form for damages:

$$\Gamma(\mathcal{CO}_t) \equiv d_3 \left(d_0 + d_1 \mathcal{CO}_t + d_2 \mathcal{CO}_t^2\right). \tag{16}$$

Following Copeland and Taylor (2004) and Shapiro and Walker (2018), firms produce pollution emissions according to a technology in which pollution is an increasing function of output and a decreasing function of abatement:

$$\xi_t(i) = \mu_j \mathcal{Z} Z_t \left[\frac{\left(1 - A_t^j(i)\right)^{\frac{\zeta-1}{\zeta}} - (1-\gamma_j)}{\gamma_j} \right]^{\frac{\zeta}{\zeta-1}} \left(N_t^j(i)\right)^{1-\alpha_j} \left(K_{t-1}^j(i)\right)^{\alpha_j}, \tag{17}$$

with $\left(1 - A_t^j(i)\right)^{\frac{\zeta-1}{\zeta}} > (1-\gamma_j)$. Here μ_j is a scaling factor, γ_j captures the firms' share of pollution emissions intensity and ζ is the elasticity of substitution between emissions and value added.

As discussed in Copeland and Taylor (2004) and Shapiro and Walker (2018), under this formulation, emissions can be interpreted as an output of production or an input into it.

They show that substituting for abatement into the production function gives rise to a Cobb-Douglas production technology that uses emissions, capital, labor, and damages to produce output. We show here that using a more general firm emission's function, equation (17), gives rise to a more general CES production function, which is given by:

$$Y_t^j(i) = \left[\gamma_j \left(\frac{\xi_t(i)}{\mu_j}\right)^{\frac{\zeta-1}{\zeta}} + (1-\gamma_j)\left\{\mathcal{Z} Z_t \left(N_t^j(i)\right)^{1-\alpha_j} \left(K_{t-1}^j(i)\right)^{\alpha_j}\right\}^{\frac{\zeta-1}{\zeta}}\right]^{\frac{\zeta}{\zeta-1}}. \qquad (18)$$

Under this representation, the pollution elasticity γ_j represents the share of emissions in firms' production. Intuitively, it measures the "dirtiness" of a firms' output. The parameter ζ determines how easy or difficult it is to substitute between emissions and other factors of production. When the value of $\zeta < 1$, emissions and value added are gross complements; when $\zeta > 1$, they are gross substitutes. As discussed below, we assume pollution regulations are sufficiently stringent for firms to engage in some form of abatement. We also assume that the only abatement cost is that of the associated diverted production.[7]

Firms are monopolistically competitive, facing downward sloping demands. Each firm chooses prices $P_t^j(i)$ and abatement investment $A_t^j(i)$, $N_t^j(i)$, and $K_{t-1}^j(i)$ to maximize profits:

$$\Phi_t^j(i) = P_t^j(i)\, Y_t^j(i) - P_t w_t N_t^j(i) - P_t r_{K,t}^j K_{t-1}^j(i) - \tau P_t \theta_t \xi_t^j(i).$$

The profit function involves several terms. A consumer or investment packer pays price $P_t^j(i)$ for good i. Each firm receives nominal revenue $P_t^j(i)\, Y_t^j(i)$. Firms' nominal costs comprise of the nominal wage bill $P_t w_t N_t^j(i)$, the nominal cost of renting physical capital $P_t r_{K,t}^j K_{t-1}^j(i)$, and the nominal cost of emissions $\tau P_t \theta_t \xi_t^j(i)$, where τ is a tax paid on emissions and θ_t the price of emissions (e.g. per ton of carbon).

We assume that only brown firms pollute and green firms do not; i.e. $\gamma_B \in (0,1)$ and $\gamma_G = 0$. Note that, although green firms are 'green' in the sense of not generating new emissions through their production, there are nevertheless emissions embodied in their capital stock, which is a composite of brown and green goods, as described above.

[7] The results are robust to the introduction of quadratic abatement costs, which reduce net production.

The first order conditions for brown firms (type B) are given by:

$$mc_t^B(i) = \frac{\left(1 - A_t^j(i)\right)^{\frac{\zeta-1}{\zeta}} w_t N_t^B(i)}{(1-\gamma_B)\, p_t^B (1-\alpha_B)\, Y_t^B(i)}, \tag{19}$$

$$mc_t^B(i) = \frac{\left(1 - A_t^j(i)\right)^{\frac{\zeta-1}{\zeta}} r_{K,t}^j K_{t-1}^B(i)}{(1-\gamma_B)\, \alpha_B p_t^B Y_t^B(i)}, \tag{20}$$

$$1-\gamma_B = \left(1 - A_t^j(i)\right)^{\frac{\zeta-1}{\zeta}} \left[1 - \gamma_B \left(\frac{p_t^B mc_t^B(i)}{\tau \theta_t \mu_B}\right)^{\zeta-1}\right]. \tag{21}$$

The problem of green firms (type G) collapses to the standard problem in models without emissions, with firms choosing prices, labor and physical capital. The first order conditions for green firms (type G) are:

$$mc_t^G(i) = \frac{w_t N_t^G(i)}{p_t^G (1-\alpha_G)\, Y_t^G(i)}, \tag{22}$$

$$mc_t^G(i) = \frac{r_{K,t}^G K_{t-1}^G(i)}{p_t^G \alpha_G Y_t^G(i)}. \tag{23}$$

We introduce price rigidities à la Calvo to investigate the short-term responses of key macroeconomic variables to carbon pricing shocks. This gives rise to a full set of New Keynesian pricing equations and short-run dynamics characterized by demand-determined output. Further details can be found in Appendix D.[8]

5.1.3 Aggregate Pollution

Aggregate atmospheric carbon ($\mathcal{CO}_t$) evolves according to the following law of motion:

$$\mathcal{CO}_t = (1-\varpi)\, \mathcal{CO}_{t-1} + \xi_t + \xi^*. \tag{24}$$

where ϖ is the depreciation of atmospheric carbon, ξ^* denote emissions from rest of the world, which is unmodelled, $\xi_t = \int_0^1 \xi_t(i)\, di$ is aggregate emissions of the brown firms in the economy that we consider, which are given by:

[8]In Appendix D we show that the real marginal cost of firms i of each type, brown or green, is the same across all firms of their respective type.

$$\xi_t = \mu_B \mathcal{Z} Z_t \left[\frac{\left(1 - A_t^B\right)^{\frac{\zeta-1}{\zeta}} - (1 - \gamma_B)}{\gamma_B} \right]^{\frac{\zeta}{\zeta-1}} \left(N_t^B\right)^{1-\alpha_B} \left(K_{t-1}^B\right)^{\alpha_B}. \tag{25}$$

5.1.4 Market Clearing

Labor market clearing is such that:

$$N_t = N_t^B + N_t^G. \tag{26}$$

Aggregate investment is defined in the same vein as aggregate output:

$$I_t = \mathcal{I}_t^B + \mathcal{I}_t^G. \tag{27}$$

Goods market clearing requires:

$$Y_t^G = C_t^G + \mathcal{G}^G + I_t^G \tag{28}$$

and:

$$Y_t^B = C_t^B + \mathcal{G}^B + I_t^B. \tag{29}$$

Aggregate output is given by:

$$Y_t = p_t^B Y_t^B + p_t^G Y_t^G, \tag{30}$$

where p_t^B and p_t^G are the relative price of brown and green goods. Finally, price inflation of brown and green goods is:

$$\Pi_t^j = \frac{p_t^j}{p_{t-1}^j} \Pi_t \text{ for } j = \{G, B\}, \tag{31}$$

and wage inflation:

$$\frac{\Pi_{w,t}}{\Pi_t} = \frac{w_t}{w_{t-1}}. \tag{32}$$

5.1.5 Climate Policy

We assume climate policy is exogenous and can be summarized by the carbon price, θ_t. Although the policy regime that we have in mind is a quantity-based cap-and-trade scheme like the EU ETS, in line with our empirical analysis, shifts in climate policy are modelled as exogenous changes in the carbon price. In particular, we assume carbon prices follow the following AR(1) process:

$$\log\left(\frac{\theta_t}{\theta}\right) = \varrho_\theta \log\left(\frac{\theta_{t-1}}{\theta}\right) + \varepsilon_{\theta t}, \quad \varepsilon_{\theta t} \sim N\left(0, \varsigma_\theta\right), \tag{33}$$

where ϱ_θ and ς_θ denote the persistence and dispersion of the shock.

5.1.6 Monetary and Fiscal Authority

The monetary authority sets policy according to the Taylor rule:

$$\frac{R_t}{R} = \left(\frac{R_{t-1}}{R}\right)^{r_r} \left[\left(\frac{\Pi_t}{\Pi}\right)^{r_\pi} \left(\frac{Y_t}{Y_t^f}\right)^{r_y}\right]^{1-r_r}, \tag{34}$$

where r_r denotes the interest rate inertia, r_π and r_y capture the degree to which monetary policy responds to inflation and the output gap. The variable Y_t^f is aggregate output in the absence of nominal rigidities.

We assume that pollution tax revenues are used to finance government expenditure ($\mathcal{G}_t$). The government runs a balanced budget:

$$\tau\theta_t\xi_t + \frac{T_t}{P_t} = \mathcal{G}_t. \tag{35}$$

5.1.7 Calibration

In this section we summarize the parameterization of the model. For the non-climate-related components of the model, the calibration is standard and consistent with the wider literature on medium-scale DSGE models, calibrated to quarterly data (see Smets and Wouters, 2007). In addition, aside from parameters γ_j and ζ, we assume that green and brown firms are symmetric. In particular, parameters governing nominal and real rigidities are the same across firm types. Moreover, we assume free labor mobility across brown and green firms, unlike Ferrari and Pagliari (2021). The full set of parameters are reported in Table 1.

Table 1 MODEL CALIBRATION

Parameter	Description	Value
β	Subjective discount factor	0.99
σ	Inverse of inter-temporal elast. of subst.	2
ϕ	Degree of consumption habits	0.75
φ	Inverse of Frisch elast.	2
χ	Disutility of labor (implied)	2.15
δ	Capital depreciation	0.025
α_j	Capital share in j	0.33
ψ_j	Investment adj. cost in j	5
$\frac{g}{y}$	Government to output ratio	0.2
ϵ_j	Elast. of subs. between goods	6
ϵ_w	Elast. of subs. between labor	11
ϑ_j	Calvo price in j	0.75
ϑ_w	Calvo wage	0.85
ι_j	Price indexation	0.25
ι_w	Wage indexation	0.25
r_r	Taylor rule inertia	0.75
r_π	Taylor rule parameter	1
r_π	Taylor rule parameter	0.15
	Climate parameters	
η	Elast. of subs. between B and G	1.5
ν	Consumption brown share	0.70
γ_B	Emission's share in B	0.34
τ	Carbon tax rate	0.15
A^B	Steady state abatement in B	0.1
ζ	Elast. of subs. between emissions and value added	0.25
μ_B	Emission's scale parameter (implied)	0.71
θ	Carbon price (implied)	6.26
$\frac{\bar{xi}}{\bar{Y}}$	Carbon intensity (implied)	0.28
ϖ	Depreciation of atmospheric carbon	0.0021
d_0	Constant in damage function	$1.3950e-3$
d_1	1st order coeff. in damage function	$-6.6722e-6$
d_2	2nd order coeff. in damage function	$1.4647e-8$
d_3	Damage function shifter	1
ρ_θ	Persistence of the shock	0.85
ς_θ	Dispersion of the shock	0.0175

Starting with the calibration of the integrated economic and carbon cycle block, we set the depreciation of atmospheric carbon (ϖ) to 0.0021 as in Heutel (2012). We also use the damage function parameters from the same study. In line with Annicchiarico and Di Dio (2015), the steady state atmospheric carbon dioxide ($\mathcal{CO}$) is set consistent with a carbon mass of about 800 gigatons in 2005. The steady state value of abatement is taken from Annicchiarico and Di Dio (2015), and set to 0.1. Conditional on the value of ϖ, the steady state level of atmospheric carbon ($\mathcal{CO}$) pins down the steady state value of emissions (ξ). We set the share of foreign emissions, ξ^*, to 0.9 of global emissions, consistent with the global share of EU emissions of around 10%.

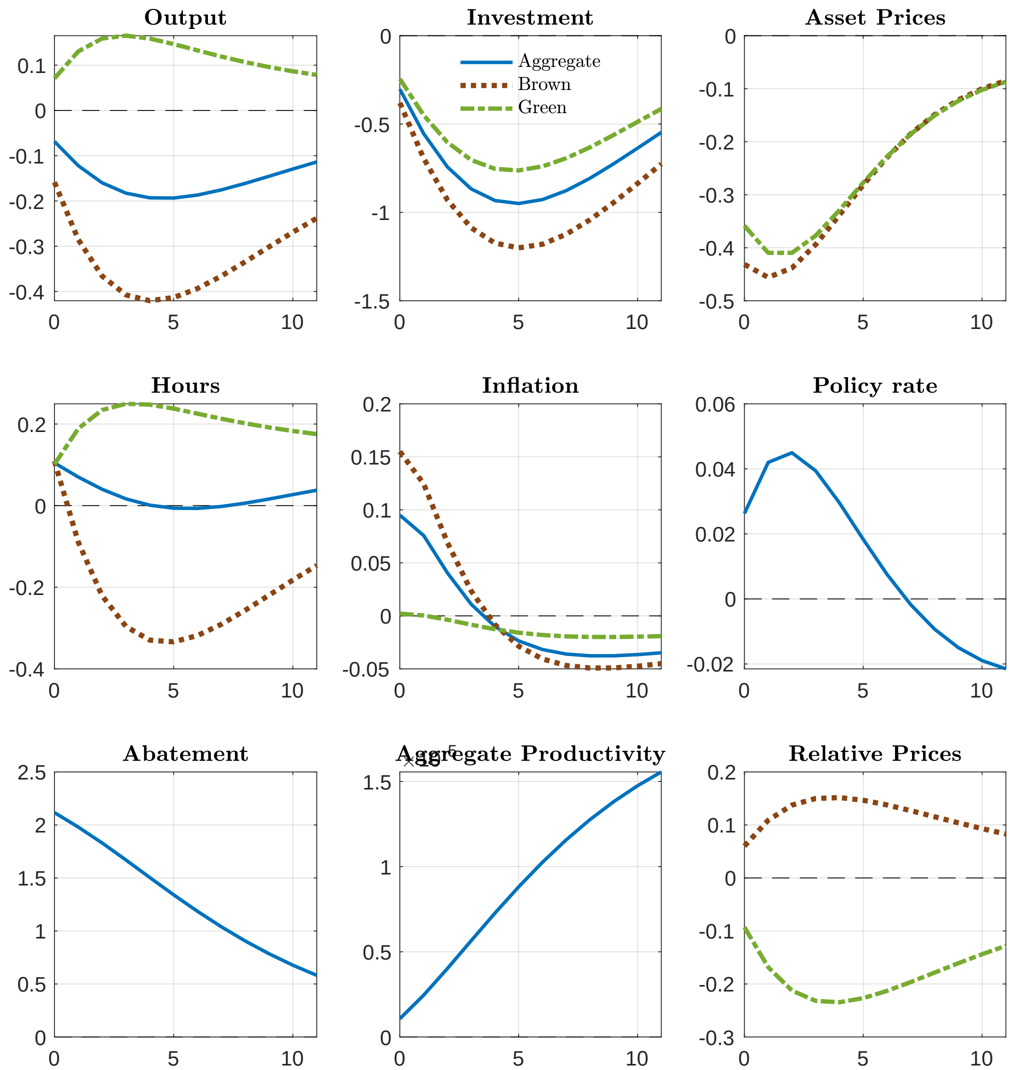
Firms' technology and household preferences include a number of further climate-related parameters. Overall, we calibrate the model so that the steady-state emissions intensity of output (i.e. $\bar{\xi}/\bar{Y}$) broadly matches the average emissions intensity of the countries we consider in the empirical analysis, which is 0.28 tonnes of CO_2 per PPP dollar of GDP. To do so, we focus on two parameters that have particular influence over steady-state emissions intensity. First, the share of brown goods in the consumption ν, which we set to 0.70. Second, the emissions share in brown firms' production (γ_b), which we set to 0.34. The pollution intensity parameter is the key difference in the technologies of brown and green firms. As described above, we set this to 0 for green firms. For the other climate-related parameters, we follow the wider literature. We set the elasticity of substitution between brown and green goods in household preferences to 1.5 as proposed by Ferrari and Pagliari (2021). The elasticity of substitution between emissions and other inputs, ζ, is set to 0.25, consistent with the Integrated Assessment Models (IAMs) literature (see, for example, Luderer et al., 2020). In addition, we set the steady state carbon tax at 0.15. Finally, the emissions scale parameter μ_B and the steady-state value of carbon prices, θ, are model-dependent.

The persistence (ϱ_θ) and dispersion of the carbon pricing shock (ς_θ) are chosen to match the trough response of aggregate output in quarter 6 ($\varrho_\theta = 0.85$ and $\varsigma_\theta = 0.0175$).

5.2 Rationalizing the results

In this section, we consider the impact of an exogenous increase in the price of emissions in the model. As described in Section 5.1.5, this experiment is the model counterpart to the shock that we consider in our empirical analysis. In line with the empirical evidence, we show that the model generates a rise in aggregate inflation, a contraction in aggregate output and heterogeneous responses in macroeconomic variables and asset prices across firms (within a given sector) after a carbon pricing shock. Figure 5 plots the responses to the shock for a selection of aggregate and good-specific variables.

Figure 5 Impulse Responses to a Carbon Pricing Shock



Note. Impulse responses of the model variables to a carbon pricing shock. Solid blue lines report the response of aggregate variables; dash-dotted green lines report the responses of green firms; and brown dotted lines report the responses of brown firms. Apart from inflation, responses are expressed in percentage deviations from steady state values.

The immediate and direct impact of the increase in the price of emissions is to raise costs for brown firms. This squeezes their margins, leading them to raise their prices, pushing up on brown inflation. This is associated with an increase in their price relative to green goods, so demand for brown goods falls. To the extent that output is demand determined in the short run, as a result of price stickiness, brown output contracts. Although brown firms are able to switch their inputs away from higher-cost emissions, particularly towards labor, which is now relatively cheaper and easier to adjust than capital, profits overall decline. In turn, the persistent decline in profits pulls down on brown firms' equity prices through a standard asset-pricing channel (in which equity prices reflect the discounted sum of expected future profits). Furthermore, the reduced expected profitability of brown firms leads to a persistent reduction in investment.[9]

Although the shock's direct effects are on brown firms, it has spillover effects onto green firms via good and factor markets. The demand for green goods rises, reflecting the fall in their relative price. The degree to which agents substitute towards greener goods depends on the elasticity of substitution between brown and green goods. See the discussion below. Consequently, green output rises. In order to support the increase in output, labor demand by the green firms must go up. Profits are squeezed, primarily as a result of the drop in relative green prices, which more than offsets the rise in green output. The fall in relative green prices helps boost consumption in the short-run but, since the contraction is persistent, investment demand contracts. An implication of the decline in green firms' profits is a fall in their equity prices, via a similar dividend-discount mechanism as described above. The reduced profitability of green firms triggers a slowdown in investment.[10]

The relative impact of the shock on green and brown firms is qualitatively consistent with the empirical evidence. In particular, on impact, brown firms see a bigger drop in their equity prices relative to green firms. Quantitatively, however, there is a divergence between the model responses and what we see in the data. In particular, in the model, asset prices of brown firms drop by two and a half times aggregate output, whereas the equivalent response is tenfold in the data. It is known that this class of models have difficulty matching quantitatively the response of asset prices.[11] The other aggregate responses also match the empirical results well. In particular, aggregate output contracts, inflation rises, there is a

[9]These results also hold true when introducing quadratic adjustment costs in abatement.

[10]Note that the responses for Tobin's Q are aligned with the responses of asset prices.

[11]DSGE models cannot account for the risk-free interest (Weil, 1989), the equity premium (Mehra and Prescott, 1985), the excess volatility puzzle, the value premium, the slope of the yield curve, or other list of related observations (Campbell, 2003). For a discussion, see Fernández-Villaverde (2010).

modest tightening in monetary policy, and asset prices fall.[12]

Another way in which the carbon price shock affects dynamics is through its indirect impact on productivity, via the damage function - equation (16). The increase in the cost of emissions induces brown firms to abate strongly, reducing the extent to which their production contributes to emissions. This leads to a fall in emissions (not shown), which in turn boosts productivity of brown and green firms. However, since these productivity gains are relatively small (and cumulate only slowly over time), the offsetting forces are not strong enough to undo the overall increase in the real marginal cost of production of brown firms over the short-term. If anything, the fall in damages helps to counter the negative impact on output and the positive impact on inflation. In addition, due to the fact that the emissions stay in the environment for extended periods of time, the impulse responses are longer lasting than in more conventional DSGE models. So, whilst the interaction between the climate and the macroeconomy does not affect by much the responses over the short-run, they introduce more persistence in the medium to long run. This is clear from the responses that only return to their steady state values after a very prolonged period of time.

In particular, the way that the climate block alters dynamics can be seen in the impulse responses for both aggregate and good-specific inflation. Figure 5 shows that aggregate inflation increases immediately after the shock but, as it starts to dissipate, the slow and continuous rise in aggregate productivity (due to lower atmospheric carbon), starts to exert downward pressure on (green, brown, and aggregate) prices. This means that the carbon pricing shock is inflationary in the short-run but deflationary over the medium to longer run. It also means that the rise in aggregate productivity is deflationary on impact but quantitatively small. The longer run deflationary pressures are evidence of this channel further down the line.

5.3 Heterogeneity in model responses to carbon pricing shock

We can also use the model to generate heterogeneity in the response to the carbon pricing shock, consistent with our empirical analysis. There are four climate-related parameters

[12] One way to generate greater responses in asset prices is to modify the household's preference specifications. Alternatively, financial frictions can be introduced, which would also help to match the response of credit spreads. We leave this for future research.

that influence the quantitative response of the model to the shock. These can explain why some countries (and firms within a given country) are affected more than others after carbon pricing shocks, as well as why we observe differences in asset price valuations between green and brown firms. Conditional on the same size shock, it can also shed light on the impact of carbon pricing policies can have on a given economy as it evolves towards a greener state.

First, carbon pricing shocks become quantitatively more important for economic activity the browner is the economy, as captured by a higher share of brown firms' goods in consumption (ν). Second, the carbon pricing shocks are also more important quantitatively the higher the value of the emissions share in brown firms' production (captured by γ_B). Third, the extent to which brown firms can switch from emissions to other inputs in response to the shock also matters for dynamics. As the carbon price increases, firms would want to substitute emissions for other inputs of production, particularly labor (because physical capital is slower and more costly to adjust). The elasticity of substitution between emissions and value added (ζ) governs their ability to do so. When emissions and value added are gross complements ($\zeta < 1$), the demand for emissions will fall alongside that of other inputs and, as a result, brown output will respond more sharply. When emissions and value added are substitutes ($\zeta > 1$), an exogenous rise in carbon prices will sharply increase the demand for labor, and brown output will contract by less. This will, in turn, affect the profitability of brown firms relative to green firms. A lower value of ζ will result in brown firms' real marginal costs rising by more, with asset valuations responding strongly. Fourth, the degree of substitutability between green and brown goods for consumers (captured by η) determines both the relative demand for brown and green goods and how aggregate demand responds to the shock. The higher the degree of substitution across goods, the lower the aggregate impact but the higher the differences between relative prices. A larger response in relative green prices (when $\eta < 1$) results in lower profitability of green firms.

To more closely examine the heterogeneity in responses to the same carbon pricing shock from the viewpoint of the model, we conduct an exercise in which we compute the responses under different aggregate carbon intensities. As in the baseline calibration, to generate heterogeneous steady-state carbon intensities, we focus on the share of brown goods in consumption (ν) and the emissions share in brown firms' production (γ_b). Specifically, we vary the values of these two parameters so that the model-implied steady-state emissions intensity of aggregate output matches the different percentiles in the distribution of emissions intensities across the countries that we consider in the empirical analysis—the 10^{th}, 25^{th}, 75^{th}, and 90^{th} percentiles, and the median. This allows us to capture the difference between higher and lower emissions intensity on macro responses, consistent with our empirical analysis. All other parameters are left unchanged. We then consider the macroeconomic responses in these different calibrations of the model to the carbon pricing shock.

Table 2 PEAK MACRO-VARIABLE RESPONSES BY CO_2 INTENSITY

		Peak Macro Variable Response			
Percentile	CO_2 intensity	GDP	Inflation	Policy Rate	Asset Price
Median	0.3	-0.23	0.11	0.055	-0.55
10^{th}	0.2	-0.051	0.026	0.011	-0.1
25^{th}	0.23	-0.091	0.046	0.02	-0.19
75^{th}	0.35	-0.32	0.16	0.078	-0.79
90^{th}	0.36	-0.35	0.17	0.086	-0.87

NOTE: This table reports the peak responses for selected macro variables under different assumptions about the CO_2 intensity of output. In particular, we vary the emissions elasticity in production, γ_b, and the share of brown goods in consumption ν so that the model-implied emissions intensities of production match those of specific percentiles in the distribution of emissions intensities across countries in the data.

Table 2 reports the peak impulse responses for aggregate output, aggregate inflation, the policy rate, and aggregate equity prices against the corresponding emissions intensities. The table shows the importance of emissions intensity in driving the heterogeneity in the macroeconomic response to the carbon pricing shock: the higher the emissions intensity of production, the greater the response of output and equity prices in particular. As in the empirical analysis, the reaction of inflation and the interest rate is more muted. This finding is qualitatively consistent with our empirical results. In other words, even in this relatively parsimonious exercise—varying a couple of parameters closely associated with the carbon intensity of production—our simple model is able to qualitatively capture the pattern observed in the empirical exercises. In reality, countries may differ along other dimensions that also affect the response to the carbon pricing shock, such as in the degree of nominal and real rigidities. In addition, the table also shows that over time, and conditional on the same shock size, greener economies are likely to suffer less from carbon pricing policies.

6 Conclusion

We provide empirical evidence on the heterogeneous effects of carbon pricing shocks. At the macro level, we find that countries with higher CO_2 intensity are more severely affected by the shocks. At the micro level, we find that firms with high within-sector levels of CO_2 emissions see their equity prices fall more than comparable firms with lower emissions.

To rationalize the empirical results we develop a theoretical framework with brown firms (which pollute) and green firms (which only pollute indirectly) and climate policy. We consider the effects of a carbon pricing shock in the model and demonstrate that we can broadly match the aggregate and firm level dynamics that we estimate in the data. In particular, in response to an increase in carbon prices, brown firms' asset prices decline by more than those of green firms. This reflects that carbon policy affects brown firms directly and that they are unable to substitute into other inputs sufficiently to offset the increase in costs from the increase in the carbon price.

Our results are important to understand the macroeconomic costs and economic channels associated with the transition towards a greener economy. Moreover, by highlighting the heterogeneous effects of environmental policies across countries, our results have potentially important implications for international coordination and the implementation of such policies.

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Appendix

A Data

The source of the macroeconomic, financial, and enviromental data is as follows:

- Real GDP: Index. Source: Datastream.
- Harmonised Index of Consumer Prices (index). Source: Eurostat.
- Energy component of the Harmonised Index of Consumer Prices (index). Source: Eurostat.
- 3-month rate (monthly average). Source: Datastream.
- Equity price index. Source: Datastream.
- Excess Bond Premium. Source: Gilchrist and Zakrajšek (2012).
- Crude oil price - Brent Europe. Source: FRED.
- Country-level CO_2 intensity. Amount of CO2 emissions per PPP dollars of GDP. Source: World Bank.
- Firm-level CO_2 emissions. Scope 1 and Scope 2 emissions ($1,000$ tonnes). Source: Datastream.

B Summary Statistics

Table B.1 Country-level CO_2 Intensity: Summary Statistics

Country	Mean	Median	Std. Dev.	5th Pctile	95th Pctile	Skew
AUT	0.25	0.27	0.08	0.13	0.39	0.02
BEL	0.34	0.33	0.15	0.16	0.58	0.23
DEU	0.33	0.31	0.13	0.15	0.56	0.43
DNK	0.32	0.29	0.17	0.10	0.59	0.34
ESP	0.27	0.29	0.09	0.14	0.40	-0.11
FIN	0.38	0.38	0.16	0.16	0.63	0.15
FRA	0.20	0.20	0.08	0.10	0.35	0.30
GBR	0.30	0.28	0.14	0.12	0.57	0.48
GRC	0.37	0.36	0.11	0.20	0.52	0.08
IRL	0.31	0.28	0.17	0.09	0.62	0.45
ITA	0.25	0.27	0.08	0.12	0.36	-0.11
NLD	0.30	0.28	0.12	0.15	0.52	0.50
NOR	0.21	0.18	0.09	0.10	0.35	0.52
PRT	0.25	0.28	0.08	0.14	0.35	-0.16
SWE	0.18	0.17	0.09	0.07	0.31	0.27
Total	0.28	0.27	0.13	0.11	0.56	0.67

Note: This table provides summary statistics on the country-level CO_2 intensity variable (kg of CO2 emissions per PPP dollars of GDP) for the 15 countries in our sample. Carbon dioxide emissions are those stemming from the burning of fossil fuels and the manufacture of cement. They include carbon dioxide produced during consumption of solid, liquid, and gas fuels and gas flaring. Source: World Bank (EN.ATM.CO2E.PP.GD).

Table B.2 FIRM-LEVEL CO_2 INTENSITY: SUMMARY STATISTICS

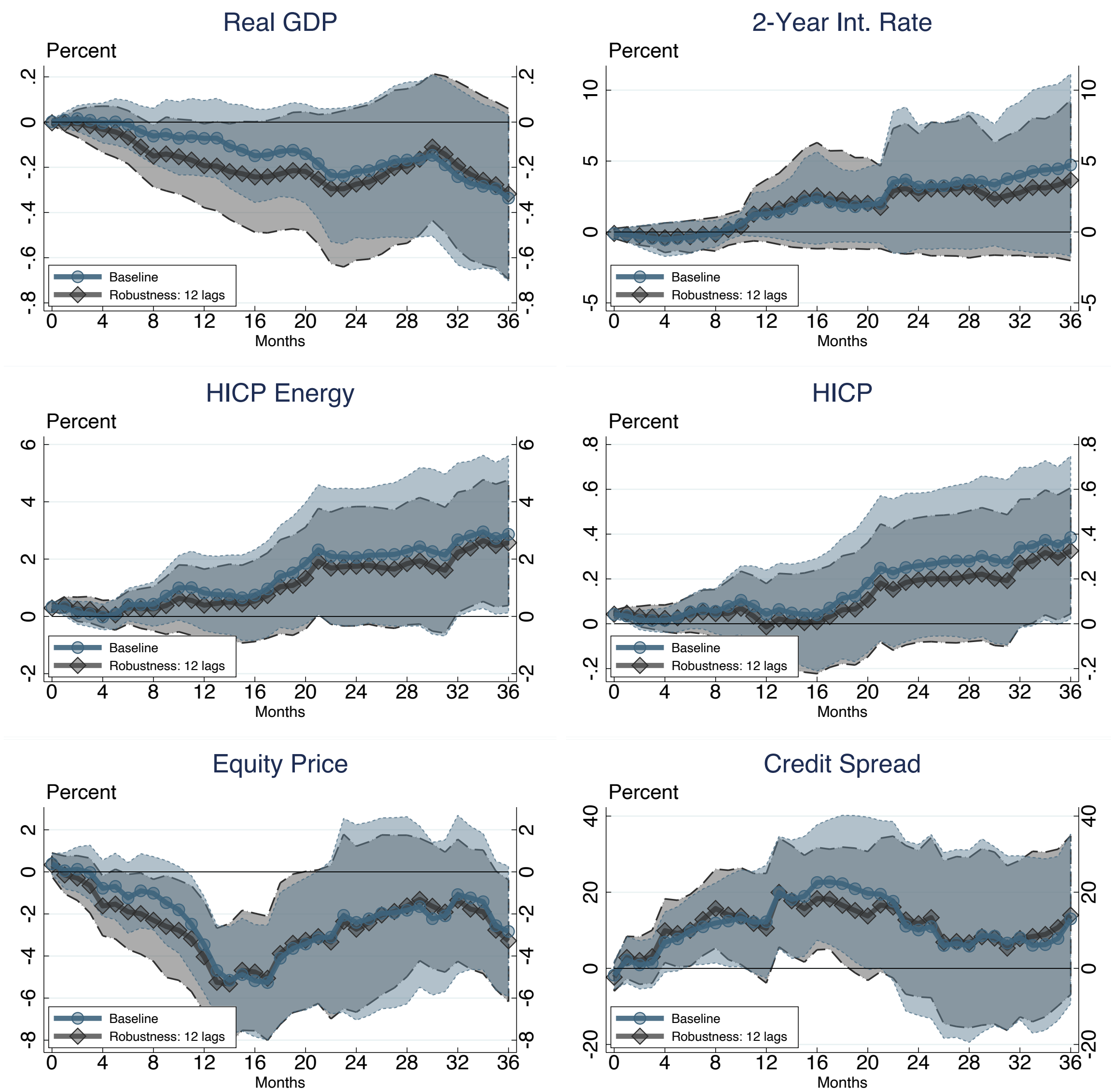
			Scope 1 CO2				Scope 2 CO2				
Country	Firms	Obs.	Mean	Median	p95	SD	Mean	Median	p95	SD	Coverage CO2
AUT	19	4009	306	50	1290	472	29	8	110	37	89.5%
BEL	20	4220	154	5	1040	319	62	6	300	114	75%
DEU	39	8229	1103	37	9170	3356	178	43	602	293	97.4%
DNK	43	5275	490	4	3702	1253	14	4	46	20	83.7%
ESP	14	2954	823	30	3546	1352	79	33	285	124	100%
FIN	38	5275	208	7	1060	628	48	10	267	89	84.2%
FRA	40	8440	1004	21	5705	3105	157	28	800	351	100%
GBR	94	19834	376	8	2380	1235	94	11	700	259	96.8%
GRC	25	5275	382	3	3257	1027	32	6	134	53	76%
ITA	71	8440	707	16	5826	2193	44	11	204	79	70.4%
IRL	33	6963	476	7	3240	905	48	2	260	78	100%
NLD	25	5275	1355	6	10500	3922	174	20	1100	416	100%
NOR	44	9284	256	8	1560	507	42	1	215	123	88.6%
PRT	15	3165	274	6	1805	573	30	13	103	40	93.3%
SWE	29	6119	27	3	87	79	22	12	71	31	96.6%

NOTE: This table provides summary statistics and coverage information on the firm-level CO_2 emission variables for the 15 countries in our sample. The CO_2 emission variable is expressed in $1,000$ tonnes. Source: Datastream.

C Robustness

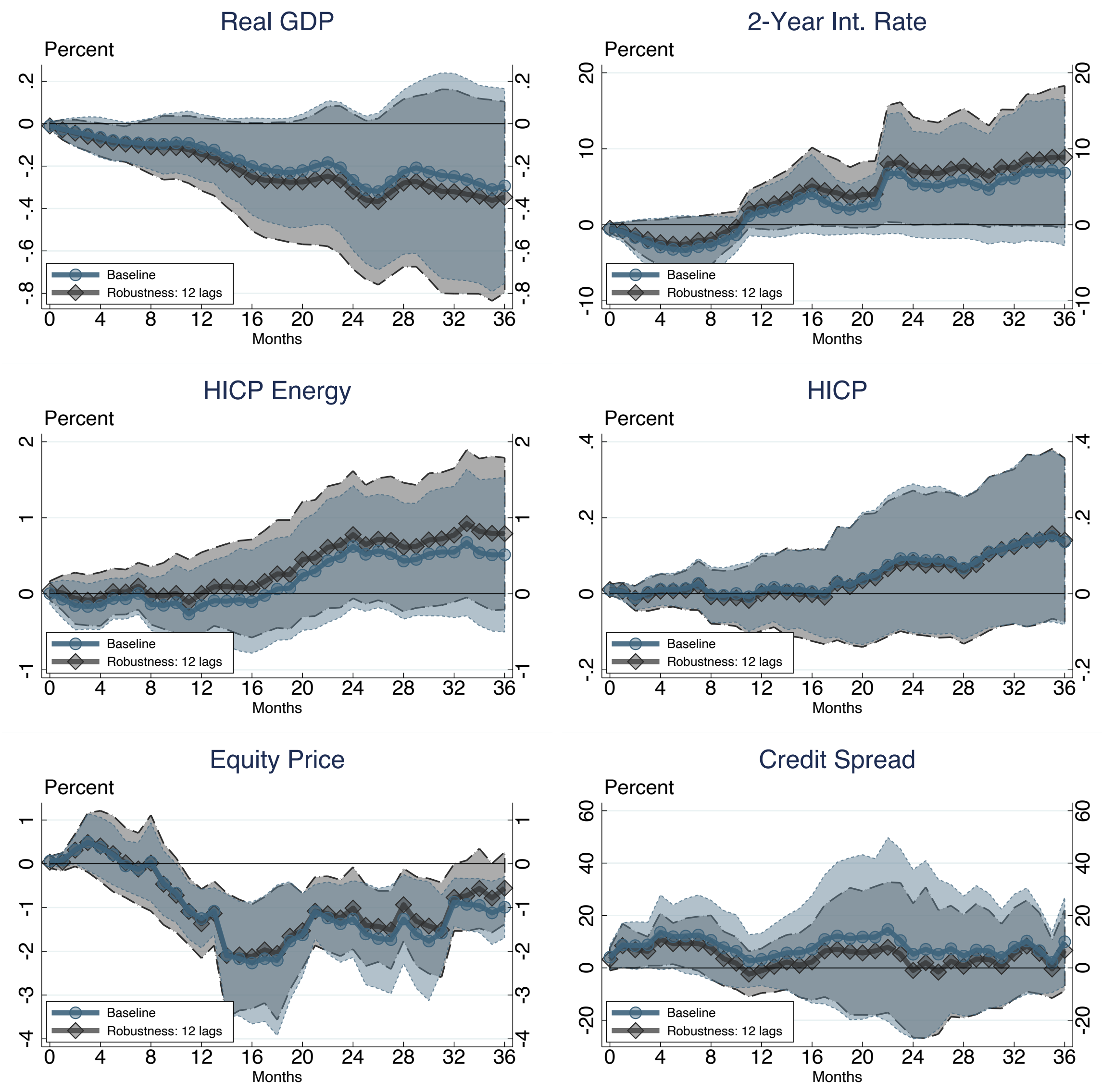
C.1 Robustness: Macro Local Projections

Figure C.1 The Effect of Carbon Pricing Shocks: Average Effect
Robustness: 12 Lags



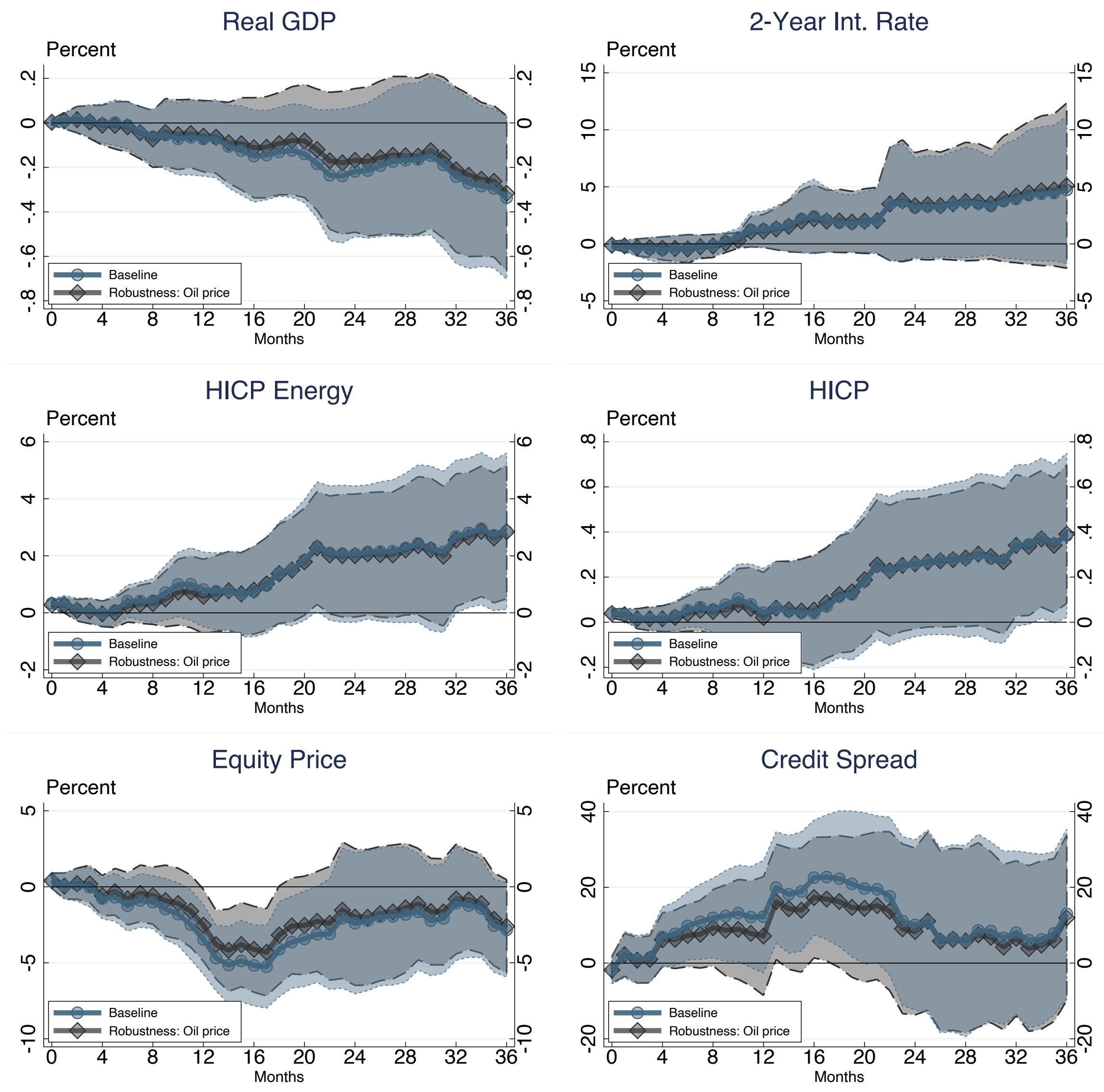
Note. Average effect of a one standard deviation increase in the carbon policy surprise (CPS) series on $y_{i,t+h}$, as captured by the coefficients β^h in equation (2). Shaded areas display 68 percent and 90 percent confidence intervals computed with heteroskedasticity and autocorrelation robust standard errors (two-way clustered, at the country-month level).

Figure C.2 The Effect of Carbon Pricing Shocks: High-emission Countries
Robustness: 12 Lags



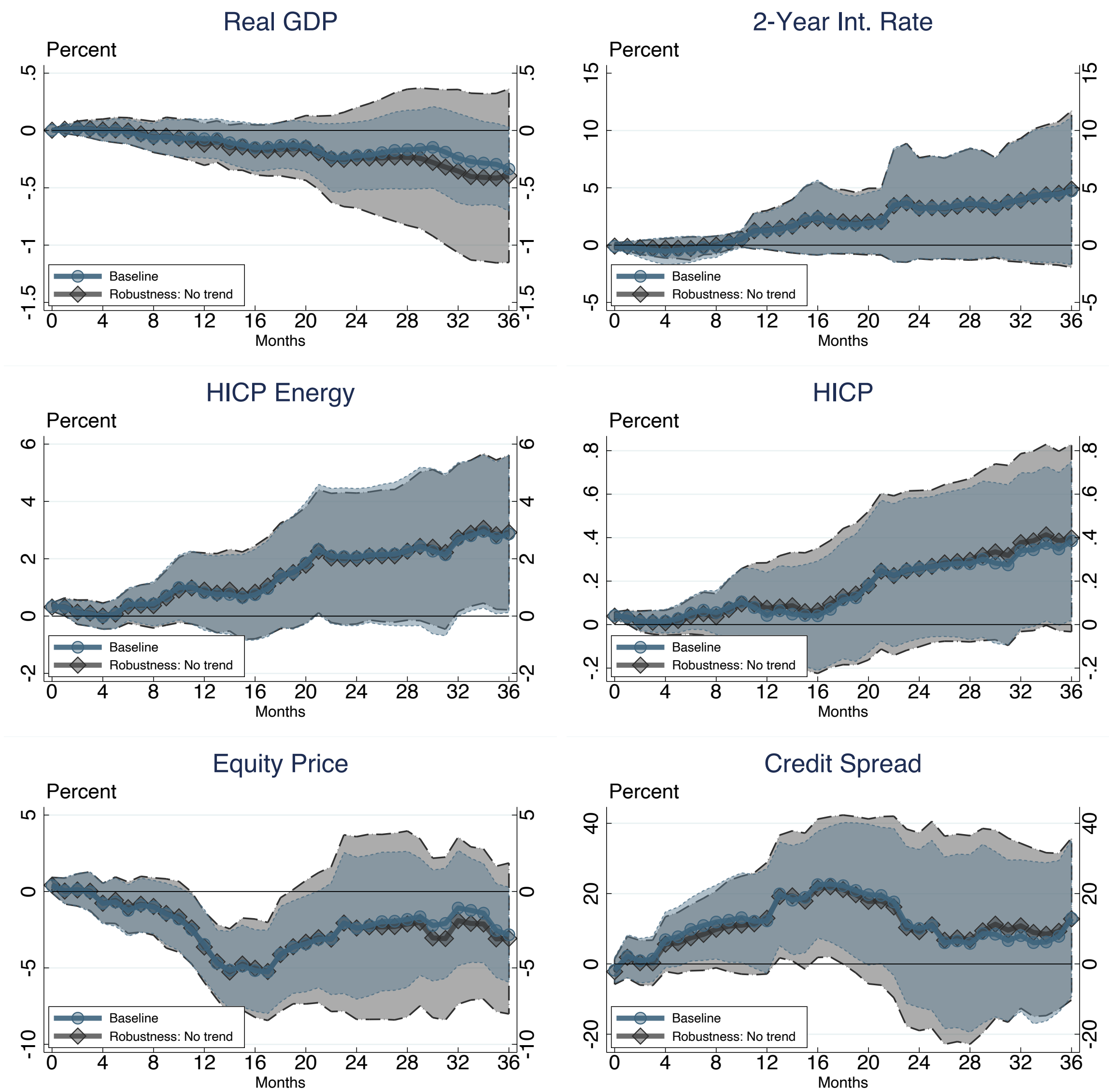
Note. Effect of a one standard deviation increase in the carbon policy surprise (CPS) series on $y_{i,t+h} - y_{i,t-1}$ for a country whose levels of CO_2 are one standard deviation above the average level of $\mathbf{CO_2}$ relative to the average country, as captured by the coefficients γ^h in equation (3). Shaded areas display 68 percent and 90 percent confidence intervals computed with heteroskedasticity and autocorrelation robust standard errors (two-way clustered, at the country-month level).

Figure C.3 The Effect of Carbon Pricing Shocks: Average Effect
Robustness: Controlling for Oil



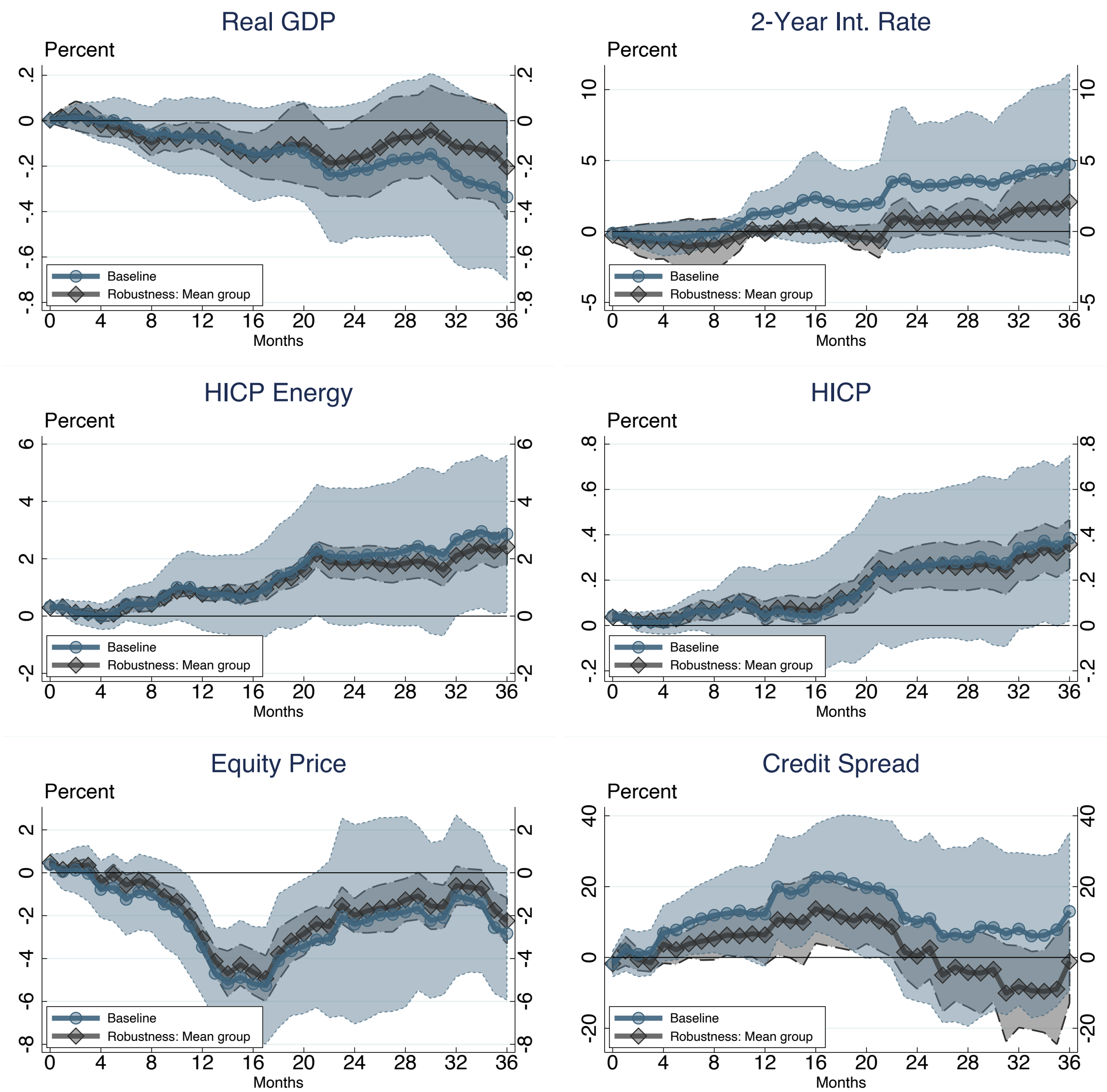
Note. Average effect of a one standard deviation increase in the carbon policy surprise (CPS) series on $y_{i,t+h}$, as captured by the coefficients β^h in equation (2). Shaded areas display 68 percent and 90 percent confidence intervals computed with heteroskedasticity and autocorrelation robust standard errors (two-way clustered, at the country-month level).

Figure C.4 The Effect of Carbon Pricing Shocks: Average Effect
Robustness: No Trend



Note. Average effect of a one standard deviation increase in the carbon policy surprise (CPS) series on $y_{i,t+h}$, as captured by the coefficients β^h in equation (2). Shaded areas display 68 percent and 90 percent confidence intervals computed with heteroskedasticity and autocorrelation robust standard errors (two-way clustered, at the country-month level).

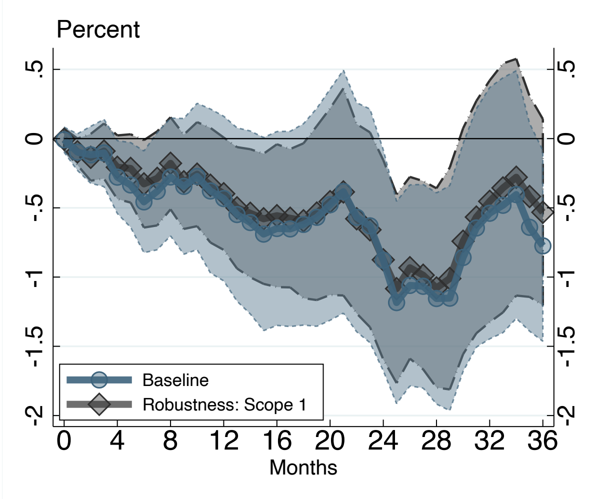
Figure C.5 The Effect of Carbon Pricing Shocks: Average Effect
Robustness: Mean Group



Note. Average effect of a one standard deviation increase in the carbon policy surprise (CPS) series on $y_{i,t+h}$, as captured by the coefficients β^h in equation (2). Shaded areas display 68 percent and 90 percent confidence intervals computed with heteroskedasticity and autocorrelation robust standard errors (two-way clustered, at the country-month level).

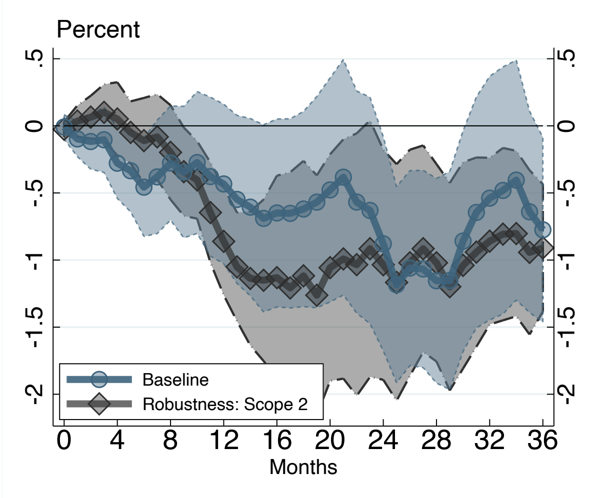
C.2 Robustness: Micro Local Projections

Figure C.6 The Effect of Carbon Pricing Shocks: High-emission Firms Robustness: Scope 1 Emissions



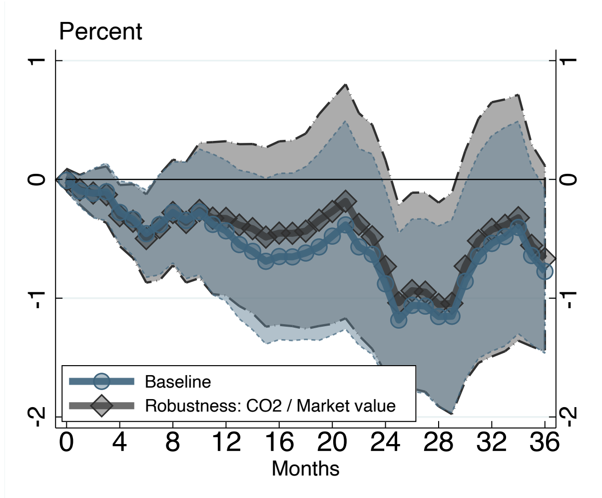
Note. Effect of a one standard deviation increase in the carbon policy surprise (CPS) series on equity prices for a high-emission firm (i.e. whose CO_2 emissions are one standard deviation above the average CO_2 emissions) relative to the average firm, as captured by the coefficients γ^h in equation (5). Shaded areas display 68 percent and 90 percent confidence intervals computed with heteroskedasticity and autocorrelation robust standard errors (two-way clustered, at the firm-month level).

Figure C.7 The Effect of Carbon Pricing Shocks: High-emission Firms Robustness: Scope 2 Emissions



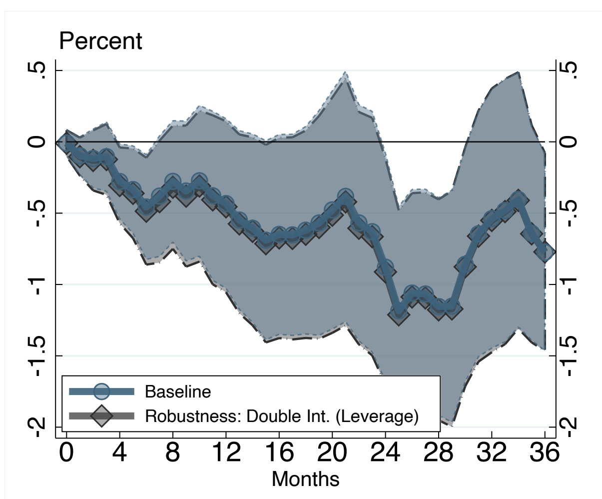
Note. Effect of a one standard deviation increase in the carbon policy surprise (CPS) series on equity prices for a high-emission firm (i.e. whose CO_2 emissions are one standard deviation above the average CO_2 emissions) relative to the average firm, as captured by the coefficients γ^h in equation (5). Shaded areas display 68 percent and 90 percent confidence intervals computed with heteroskedasticity and autocorrelation robust standard errors (two-way clustered, at the firm-month level).

Figure C.8 The Effect of Carbon Pricing Shocks: High-emission Firms
Robustness: Emissions Normalized by Market Value



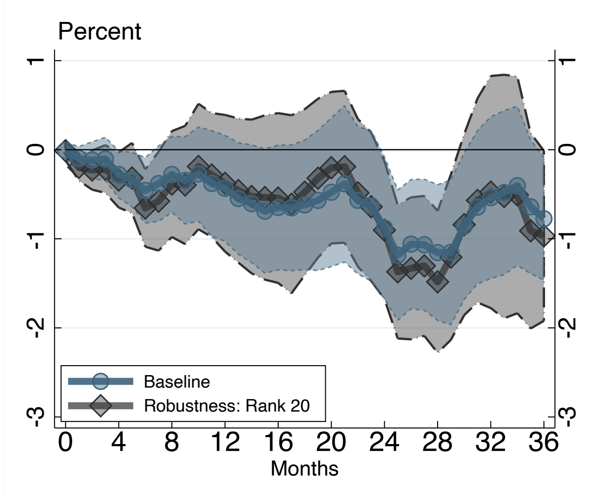
Note. Effect of a one standard deviation increase in the carbon policy surprise (CPS) series on equity prices for a high-emission firm (i.e. whose CO_2 emissions are one standard deviation above the average CO_2 emissions) relative to the average firm, as captured by the coefficients γ^h in equation (5). Shaded areas display 68 percent and 90 percent confidence intervals computed with heteroskedasticity and autocorrelation robust standard errors (two-way clustered, at the firm-month level).

Figure C.9 The Effect of Carbon Pricing Shocks: High-emission Firms
Robustness: Double Interaction Leverage



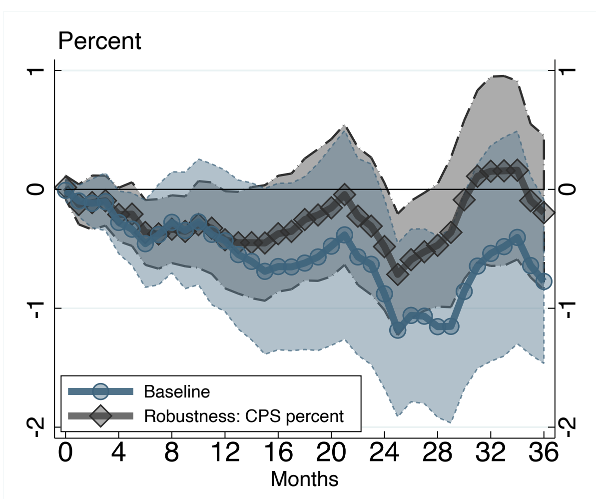
Note. Effect of a one standard deviation increase in the carbon policy surprise (CPS) series on equity prices for a high-emission firm (i.e. whose CO_2 emissions are one standard deviation above the average CO_2 emissions) relative to the average firm, as captured by the coefficients γ^h in equation (5). Shaded areas display 68 percent and 90 percent confidence intervals computed with heteroskedasticity and autocorrelation robust standard errors (two-way clustered, at the firm-month level).

Figure C.10 The Effect of Carbon Pricing Shocks: High-emission Firms
Robustness: Top20 Firms



Note. Effect of a one standard deviation increase in the carbon policy surprise (CPS) series on equity prices for a high-emission firm (i.e. whose CO_2 emissions are one standard deviation above the average CO_2 emissions) relative to the average firm, as captured by the coefficients γ^h in equation (5). Shaded areas display 68 percent and 90 percent confidence intervals computed with heteroskedasticity and autocorrelation robust standard errors (two-way clustered, at the firm-month level).

Figure C.11 The Effect of Carbon Pricing Shocks: High-emission Firms
Robustness: CPS Surprise (Percent)



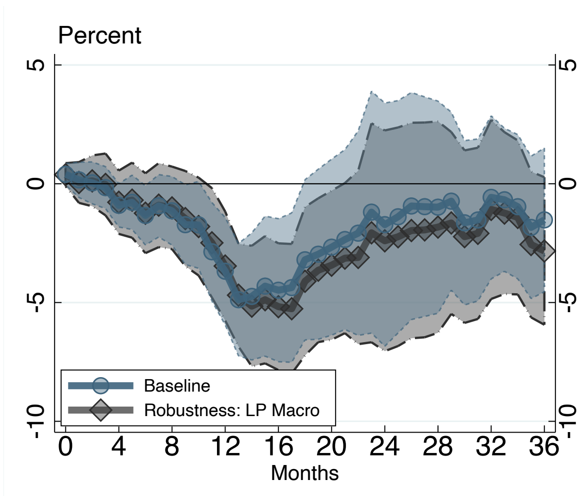
Note. Effect of a one standard deviation increase in the carbon policy surprise (CPS) series on equity prices for a high-emission firm (i.e. whose CO_2 emissions are one standard deviation above the average CO_2 emissions) relative to the average firm, as captured by the coefficients γ^h in equation (5). Shaded areas display 68 percent and 90 percent confidence intervals computed with heteroskedasticity and autocorrelation robust standard errors (two-way clustered, at the firm-month level).

C.3 Additional Results: Comparison Between Micro and Macro Estimates

As typically done for 'macro' exercises that use 'micro' data, in this section we compare the impulse responses we obtain from the country-level data with the impulse responses we obtain from firm-level data.

Average Response: Macro vs. Micro We start by comparing the average effect of carbon pricing shocks on equity prices in the 'macro' (i.e. country-level) and 'micro' (i.e. firm-level) data, as captured by the β^h coefficients in equations (2) and (4). Figure C.12, which reports the impulse responses, shows that the micro and macro evidence are very well aligned.

Figure C.12 THE EFFECT OF CARBON PRICING SHOCKS: FIRM-LEVEL RESPONSES
AVERAGE RESPONSE: COMPARISON WITH COUNTRY-LEVEL DATA



NOTE. Effect of a one standard deviation increase in the carbon policy surprise (CPS) series on equity prices in the firm-level data (blue), as captured by the coefficients β^h in equation (4); and in the country-level data (black), as captured by the coefficients β^h in equation (2). Shaded areas display 68 percent and 90 percent confidence intervals computed with heteroskedasticity and autocorrelation robust standard errors (two-way clustered, at the firm-month level).

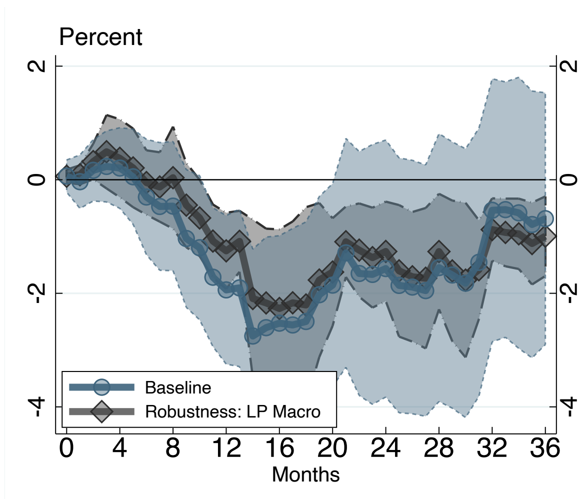
Relative Response of High-emission Countries: Macro vs. Micro The cross-sectional evidence in the country-level analysis suggests that the drop in equity prices is larger in countries with higher CO2 intensity (see Figure 2). Do we find a similar pattern when using the firm-level data? To investigate this, we employ the country-level CO_2 emission variable, $CO2_{it}$, in the following specification:

$$q_{ij,t+h} - q_{ij,t-1} = \alpha_i^h + \alpha_t^h + \gamma^h(CPS_t \times CO2_{i,t-1}) + \sum_{p=1}^{P} \gamma_p^h X_{i,t} + \sum_{p=1}^{P} \Theta_p^h Z_{ij,t} + u_{ij,t+h}, \quad \text{(C.1)}$$

where $\alpha_{i,h}^h$ is a country fixed effect at horizon h; α_t^h is a time fixed effect at horizon h; CPS_t is the carbon pricing shock; $CO2_{i,t}$ is the country-level carbon intensity measure described above; and $X_{i,t}$ collects all additional controls, including lags of the outcome variable and of the other macro aggregates in our data set (namely, log real GDP, log headline HICP, log energy HICP, a log index of equity prices, and the two-year interest rate); $Z_{ij,t}$ is a vector of firm-level controls. To facilitate the interpretation of the estimated coefficient γ^h, we standardize the country's carbon intensity variable over the entire sample, so its units are standard deviations in our sample. Standard errors are clustered two-way, at the country-month level.

Figure C.13 compares the relative effect of carbon pricing shocks on equity prices for a high-emission country in the 'macro' (i.e. country-level) and 'micro' (i.e. firm-level) data, as captured by the γ^h coefficients in equations (3) and (C.1). The impulse response are remarkably similar, thus lending support to the country-level evidence.

Figure C.13 The Effect of Carbon Pricing Shocks: Firm-level Responses Comparison with Country-level Data: High $C0_2$ Countries



Note. Relative effect of a one standard deviation increase in the carbon policy surprise (CPS) series on equity prices for a high-emission country in the firm-level data (blue), as captured by the coefficients γ^h in equation (C.1); and in the country-level data (black), as captured by the coefficients γ^h in equation (3). Shaded areas display 68 percent and 90 percent confidence intervals computed with heteroskedasticity and autocorrelation robust standard errors (two-way clustered, at the country-month level).

D Model

D.1 Labor Unions

Aggregate labor demand is given by:

$$N_t^d = \left[\int_0^1 N_t(\omega)^{\frac{\epsilon_w - 1}{\epsilon_w}} d\omega\right]^{\frac{\epsilon_w}{\epsilon_w - 1}},$$

where ϵ_w is the elasticity of substitution across labor varieties. The labor union maximizes

$$\max_{w_t^*} \mathbb{E}_t \sum_{s=t}^{\infty} (\beta\vartheta_w)^{s-t} \left\{ -\chi \frac{N_s(\omega)^{1+\varphi}}{1+\varphi} + \Lambda_s \prod_{s=1}^{j} \left(\frac{\Pi_{s-1}^{\iota_w} \Pi^{1-\iota_w}}{\Pi_s}\right) w_s(\omega) N_s(\omega) \right\},$$

subject to the following demand schedule:

$$N_s(\omega) = \left(\prod_{k=1}^{s} \frac{w_s(\omega)}{w_s} \frac{\Pi_{s-1}^{\iota_w} \Pi^{1-\iota_w}}{\Pi_s}\right)^{-\epsilon_w} N_s^d.$$

The problem of the union is to maximize profits,

$$\max_{w_t^*} \mathbb{E}_t \sum_{s=t}^{\infty} (\beta\vartheta_w)^{s-t} \left\{ -\chi \frac{\left[\left(\frac{w_t(\omega)}{w_s} \prod_{k=1}^{s} \frac{\Pi_{s-1}^{\iota_w} \Pi^{1-\iota_w}}{\Pi_s}\right)^{-\epsilon_w} N_s^d\right]^{1+\varphi}}{1+\varphi} + \right.$$
$$\left. + \Lambda_s w_s \left(\frac{w_t(\omega)}{w_s} \prod_{k=1}^{s} \frac{\Pi_{w,s-1}^{\iota_w} \Pi^{1-\iota_w}}{\Pi_s}\right)^{1-\epsilon_w} N_s^d \right\}.$$

The first order condition with respect to w_t^* can be expressed in recursive form by separating the LHS from the RHS of the first order condition.

$$\mathcal{F}_t^w = \epsilon_w \chi (\tilde{w}_t)^{-\epsilon_w(1+\varphi)} \left(N_t^d\right)^{1+\varphi} + \beta\vartheta_w \mathbb{E}_t \left(\frac{\Pi_t^{\iota_w} \Pi^{1-\iota_w}}{\Pi_{t+1}}\right)^{-\epsilon_w(1+\varphi)} \left(\frac{\tilde{w}_{t+1}}{\tilde{w}_t}\right)^{\epsilon_w(1+\varphi)} \mathcal{F}_{t+1}^w, \tag{D.1}$$

$$\mathcal{J}_t^w = (\epsilon_w - 1) \Lambda_t (\tilde{w}_t)^{1-\epsilon_w} w_t N_t^d + \beta\vartheta_w \mathbb{E}_t \left(\frac{\Pi_t^{\iota_w} \Pi^{1-\iota_w}}{\Pi_{t+1}}\right)^{1-\epsilon_w} \left(\frac{\tilde{w}_{t+1}}{\tilde{w}_t}\right)^{\epsilon_w - 1} \mathcal{J}_{t+1}^w, \tag{D.2}$$

$$\mathcal{J}_t^w = \mathcal{F}_t^w, \tag{D.3}$$

where $\tilde{w}_t = \frac{w_t^*}{w_t}$ is the optimal wage divided by the aggregate wage rate. The aggregate law of motion for wages is therefore equal to:

$$w_t^{1-\epsilon_w} = \vartheta_w \left(\frac{\Pi_{t-1}^{\iota_w} \Pi^{1-\iota_w}}{\Pi_t} w_{t-1}\right)^{1-\epsilon_w} + (1-\vartheta_w) (w_t^*)^{1-\epsilon_w}. \tag{D.4}$$

D.2 Capital Producers

Capital producers provide investment goods to brown and green firms by combining green and brown investment. Aggregate investment is

$$I_t = \left\{ \nu^{\frac{1}{\eta}} \left(I_t^B \right)^{\frac{\eta-1}{\eta}} + (1-\nu)^{\frac{1}{\eta}} \left(I_t^G \right)^{\frac{\eta-1}{\eta}} \right\}^{\frac{\eta}{\eta-1}} .$$

Profits are:

$$\Pi_t = I_t - p_t^B I_t^B - p_t^G I_t^G .$$

and the demand schedules are given by

$$I_t^B = \nu \left(p_t^B \right)^{-\eta} I_t, \tag{D.5}$$

$$I_t^G = (1-\nu) \left(p_t^G \right)^{-\eta} I_t. \tag{D.6}$$

D.3 Firms

Solving for $1 - A_t^j(i)$ and substituting into the production function, we can write a CES function combining pollution emissions and productive factors:

$$Y_t^j(i) = \left[\gamma_j \left(\frac{\xi_t(i)}{\mu_j} \right)^{\frac{\zeta-1}{\zeta}} + (1-\gamma_j) \left[Z_t \left(N_t^j(i) \right)^{1-\alpha_j} \left(K_{t-1}^j(i) \right)^{\alpha_j} \right]^{\frac{\zeta-1}{\zeta}} \right]^{\frac{\zeta}{\zeta-1}} .$$

In this interpretation, γ_j is the share for pollution emissions and ζ_j the elasticity of substitution between emissions and value added. Theory and evidence do not give clear guidance on how to think about pollution emissions in the firm's environmental decisions. Is pollution a second output on which firms are taxed via environmental regulation? Or is pollution best thought of an input to production, which has a price due to environmental regulation? Or alternatively, should we think of firms as optimizing standard production decisions subject to a constraint on pollution emissions? An advantage of this framework is that it does not require choosing one of these interpretations as correct and the others as incorrect, since these interpretations are equivalent. For the operating firm, pollution emissions decline when firms reallocates productive factors to abatement investment. The model accounts for several ways in which firms and consumer behavior affect pollution emissions: consumption, investment and production all respond to environmental regulation, and all of these forces can interact to determine pollution emissions.

One concept that is commonly discussed is that the number of workers per unit of output, $\frac{Y_t^B(i)}{N_t^B(i)} = \left(1 - A_t^B(i)\right) \left(N_t^j(i) \right)^{-\alpha_B} \left(K_{t-1}^j(i) \right)^{\alpha_B}$ respond to environmental regulation. This depends on environmental regulation since it increases the shares allocated to abatement rather than producing output.

Firm i of type j solves the following problem,

$$\min_{A_t^B(i), N_t^B(i), K_{t-1}^B(i)} P_t w_t N_t^B(i) + P_t r_{K,t}^B K_{t-1}^B(i) + \tau P_t \theta_t^B \xi_t(i)$$

subject to equation (15). The first order conditions of brown firms are given by:

$$mc_t^B(i) = \frac{\tau\theta_t\mu_B}{p_t^B\gamma_B}\left[\frac{\left(1-A_t^j(i)\right)^{\frac{\zeta-1}{\zeta}}-(1-\gamma_B)}{\gamma_B}\right]^{\frac{\zeta}{\zeta-1}-1}\left(1-A_t^j(i)\right)^{\frac{\zeta-1}{\zeta}-1},$$

$$mc_t^B(i) = \frac{w_t N_t^B(i)}{(1-\alpha_B)p_t^B Y_t^B(i)} + \frac{\tau\theta_t^B}{p_t^B}\mu_B\left[\frac{\left(1-A_t^B(i)\right)^{\frac{\zeta-1}{\zeta}}-(1-\gamma_B)}{\gamma_B}\right]^{\frac{\zeta}{\zeta-1}}\frac{1}{1-A_t^B(i)},$$

$$mc_t^B(i) = \frac{r_{K,t}^B K_{t-1}(i)}{\alpha_B p_t^B Y_t^B(i)} + \frac{\tau\theta_t^B}{p_t^B}\mu_B\left[\frac{\left(1-A_t^B(i)\right)^{\frac{\zeta-1}{\zeta}}-(1-\gamma_B)}{\gamma_B}\right]^{\frac{\zeta}{\zeta-1}}\frac{1}{1-A_t^B(i)},$$

where $mc_t^B(i)$ is the real marginal cost of firm i of type B. The real marginal cost of brown firms is therefore,

$$mc_t^B(i) = mc_t^B = \frac{1}{p_t^B}\left[(\gamma_B)^\zeta(\tau\theta_t\mu_B)^{1-\zeta} + (1-\gamma_B)^\zeta Z_t^{\zeta-1}\left[\left(\frac{w_t}{1-\alpha_B}\right)^{1-\alpha_j}\left(\frac{r_{K,t}^j}{\alpha_B}\right)^{\alpha_j}\right]^{1-\zeta}\right]^{\frac{1}{1-\zeta}}.$$

Equally, the real marginal cost of production of green firms can be obtained by substituting the first order conditions into the production function,

$$mc_t^G = \frac{1}{Z_t p_t^G}\left[\frac{w_t}{(1-\alpha_G)}\right]^{1-\alpha_G}\left(\frac{r_{K,t}^G}{\alpha_G}\right)^{\alpha_G}. \tag{D.7}$$

The Phillips curve for type-j firms is given by the following set of equations,

$$\mathcal{J}_t^j = \Lambda_t mc_t^j Y_t^j + \beta\vartheta_j\mathbb{E}_t\frac{\Pi_{t+1}^j}{\Pi_{t+1}}\left(\frac{\Pi_{t+1}^j}{\left(\Pi_t^j\right)^{\iota_j}\Pi^{1-\iota_j}}\right)^{\epsilon_j}\mathcal{J}_{t+1}^j, \tag{D.8}$$

$$\mathcal{F}_t^j = \Lambda_t\tilde{p}_t^j Y_t^j + \beta\vartheta_j\mathbb{E}_t\frac{\Pi_{t+1}^j}{\Pi_{t+1}}\left(\frac{\Pi_{t+1}^j}{\left(\Pi_t^j\right)^{\iota_j}\Pi^{1-\iota_j}}\right)^{\epsilon_j-1}\mathcal{F}_{t+1}^j, \tag{D.9}$$

$$\mathcal{J}_t^j = \tilde{p}_t^j\frac{\epsilon_j-1}{\epsilon_j}\mathcal{F}_t^j, \tag{D.10}$$

$$1 = \vartheta_j\left(\frac{\Pi_t^j}{\left(\Pi_{t-1}^j\right)^{\iota_j}\Pi^{1-\iota_j}}\right)^{\epsilon_j-1} + (1-\vartheta_j)\left(\tilde{p}_t^j\right)^{1-\epsilon_j}. \tag{D.11}$$

D.4 Market Clearing

Labor market clearing is such that:

$$N_t = \Delta_{w,t}\left(N_t^B + N_t^G\right). \tag{D.12}$$

where $\Delta_{w,t}$ denotes the wage dispersion, which evolves according to:

$$\Delta_{w,t} = (1-\vartheta_w)(\tilde{w}_t)^{-\epsilon_w} + \vartheta_w \left(\frac{\Pi_{t-1}^{\iota_w}\Pi^{1-\iota_w}}{\Pi_t}\right)^{-\epsilon_w} \left(\frac{w_{t-1}}{w_t}\right)^{-\epsilon_w} \Delta_{w,t-1}. \tag{D.13}$$

The price dispersion for firms of j type evolves as follows:

$$\Delta_t^j = (1-\vartheta_j)\left(\tilde{p}_t^j\right)^{-\epsilon_j} + \vartheta_j \left(\frac{\Pi_t^j}{\left(\Pi_{t-1}^j\right)^{\iota_j}\Pi^{1-\iota_j}}\right)^{\epsilon_j} \Delta_{t-1}^j \quad \text{for} j = \{B, G\}. \tag{D.14}$$

Market clearing in the investment market is:

$$I_t = \mathcal{I}_t^B + \mathcal{I}_t^G, \tag{D.15}$$

Goods market clearing requires:

$$Y_t^G = C_t^G + \mathcal{G}_t^G + I_t^G \tag{D.16}$$

and

$$Y_t^B = C_t^B + \mathcal{G}_t^B + I_t^B. \tag{D.17}$$

Finally, price inflation is:

$$\Pi_t^j = \frac{p_t^j}{p_{t-1}^j}\Pi_t \text{ for } j = \{G, B\}, \tag{D.18}$$

and wage inflation:

$$\frac{\Pi_{w,t}}{\Pi_t} = \frac{w_t}{w_{t-1}}. \tag{D.19}$$

D.5 Model aggregation

Market clearing. Integrating over ω gives:

$$C_t + \sum_{j=\{B,G\}} \mathcal{I}_t^j = w_t N_t + \sum_{j=\{B,G\}} \left\{ r_{K,t}^j K_{t-1}^j + \frac{\Phi_t^j}{P} \right\} - T_t.$$

Aggregate profits of brown firms are given by:

$$\frac{\Phi_t^B}{P_t} = \frac{P_t^B}{P_t} \int_0^1 \frac{P_t^B(i)}{P_t^B} Y_t^j(i)\, di - w_t N_t^B - r_{K,t}^B K_{t-1}^B - \tau\theta_t\xi_t^B,$$
$$\frac{\Phi_t^B}{P_t} = p_t^B Y_t^B - w_t N_t^B - r_{K,t}^B K_{t-1}^B - \tau\theta_t\xi_t^B.$$

Equally, aggregate profits of green firms are:

$$\frac{\Phi_t^G}{P_t} = p_t^G Y_t^G - w_t N_t^G - r_{K,t}^G K_{t-1}^G.$$

Substituting aggregate profits into the budget constraint yields:

$$
\begin{aligned}
C_t + I_t &= p_t^B Y_t^B + p_t^G Y_t^G - \tau\theta_t \xi_t^B - T_t, \\
C_t + I_t &= p_t^B Y_t^B + p_t^G Y_t^G - \tau\theta_t \xi_t^B - \mathcal{G}_t + \tau\theta_t \xi_t^B, \\
C_t + I_t + \mathcal{G}_t &= p_t^B Y_t^B + p_t^G Y_t^G.
\end{aligned}
$$

Aggregate production. Using the CES production function, we can derive aggregate output for green firms,

$$
\begin{aligned}
\int_0^1 Z_t \left(N_t^G(i)\right)^{1-\alpha_G} \left(K_{t-1}^G(i)\right)^{\alpha_G} di &= \int_0^1 \left(\frac{P_t^G(i)}{P_t^G}\right)^{-\epsilon} Y_t^G di, \\
N_t^G \int_0^1 Z_t \left(\frac{K_{t-1}^G}{N_t^G}\right)^{\alpha_G} di &= Y_t^G \int_0^1 \left(\frac{P_t^G(i)}{P_t^G}\right)^{-\epsilon} di, \\
Z_t \left(N_t^G\right)^{1-\alpha_G} \left(K_{t-1}^G\right)^{\alpha_G} &= \Delta_t^G Y_t^G.
\end{aligned}
$$

Aggregation across green firms is obtained using the first order condition with respect to abatement, which is not specific to brown firms. Equation (D.7) entails that real marginal cost and, therefore, abatement are the same across brown firms. This in turn implies that:

$$
\begin{aligned}
\int_0^1 Z_t \left(1 - A_t^B(i)\right) \left(N_t^B(i)\right)^{1-\alpha_B} \left(K_{t-1}^B(i)\right)^{\alpha_B} di &= \int_0^1 \left(\frac{P_t^B(i)}{P_t^B}\right)^{-\epsilon} Y_t^B di, \\
Z_t \left(1 - A_t^B\right) \int_0^1 \left(N_t^B(i)\right)^{1-\alpha_B} \left(K_{t-1}^B(i)\right)^{\alpha_B} di &= \int_0^1 \left(\frac{P_t^B(i)}{P_t^B}\right)^{-\epsilon} Y_t^B di, \\
Z_t \left(1 - A_t^B\right) N_t^B \int_0^1 \left(\frac{K_{t-1}^B}{N_t^B}\right)^{\alpha_B} di &= \int_0^1 \left(\frac{P_t^B(i)}{P_t^B}\right)^{-\epsilon} Y_t^B di, \\
Z_t \left(1 - A_t^B\right) \left(N_t^B\right)^{1-\alpha_B} \left(K_{t-1}^B\right)^{\alpha_B} &= \Delta_t^B Y_t^B.
\end{aligned}
$$

E Dynamic equations

The system of equations is given by:

$$
\Lambda_t = \left(C_t - \phi C_{t-1}\right)^{-\sigma} - \beta\phi \mathbb{E}_t \left(C_{t+1} - \phi C_t\right)^{-\sigma}, \tag{E.1}
$$

$$
\Lambda_t = \beta \mathbb{E}_t \left\{ \frac{R_t}{\Pi_{t+1}} \Lambda_{t+1} \right\}, \tag{E.2}
$$

$$
Q_t^B = \beta \mathbb{E}_t \frac{\Lambda_{t+1}}{\Lambda_t} \left\{ r_{K,t+1}^B + (1 - \delta_K) Q_{t+1}^B \right\}, \tag{E.3}
$$

$$
Q_t^G = \beta \mathbb{E}_t \frac{\Lambda_{t+1}}{\Lambda_t} \left\{ r_{K,t+1}^G + (1 - \delta_K) Q_{t+1}^G \right\}, \tag{E.4}
$$

$$1 = Q_t^B \left[1 - \frac{\psi_I^B}{2}\left(\frac{\mathcal{I}_t^B}{\mathcal{I}_{t-1}^B} - 1\right)^2 - \psi_I^B \left(\frac{\mathcal{I}_t^B}{\mathcal{I}_{t-1}^B} - 1\right)\frac{\mathcal{I}_t^B}{\mathcal{I}_{t-1}^B}\right] + $$
$$+ \beta \mathbb{E}_t \left\{Q_{t+1}^B \frac{\Lambda_{t+1}}{\Lambda_t}\psi_I^B \left(\frac{\mathcal{I}_t^B}{\mathcal{I}_{t-1}^B} - 1\right)\left(\frac{\mathcal{I}_t^B}{\mathcal{I}_{t-1}^B}\right)^2\right\}, \tag{E.5}$$

$$1 = Q_t^G \left[1 - \frac{\psi_I^G}{2}\left(\frac{\mathcal{I}_t^G}{\mathcal{I}_{t-1}^G} - 1\right)^2 - \psi_I^B \left(\frac{\mathcal{I}_t^G}{\mathcal{I}_{t-1}^G} - 1\right)\frac{\mathcal{I}_t^G}{\mathcal{I}_{t-1}^G}\right] + $$
$$+ \beta \mathbb{E}_t \left\{Q_{t+1}^G \frac{\Lambda_{t+1}}{\Lambda_t}\psi_I^G \left(\frac{\mathcal{I}_t^G}{\mathcal{I}_{t-1}^G} - 1\right)\left(\frac{\mathcal{I}_t^G}{\mathcal{I}_{t-1}^G}\right)^2\right\}, \tag{E.6}$$

$$K_t^B = (1 - \delta_K) K_{t-1}^B + \left(1 - \frac{\psi_B}{2}\left(\frac{\mathcal{I}_t^B}{\mathcal{I}_{t-1}^B} - 1\right)^2\right)\mathcal{I}_t^B, \tag{E.7}$$

$$K_t^G = (1 - \delta_K) K_{t-1}^G + \left(1 - \frac{\psi_G}{2}\left(\frac{\mathcal{I}_t^G}{\mathcal{I}_{t-1}^G} - 1\right)^2\right)\mathcal{I}_t^G, \tag{E.8}$$

$$\mathcal{F}_t^w = \epsilon_w \chi \left(\tilde{w}_t\right)^{-\epsilon_w(1+\varphi)}\left(\frac{N_t}{\Delta_t^w}\right)^{1+\varphi} + \beta \vartheta_w \mathbb{E}_t \left(\frac{\Pi_t^{\iota_w}\Pi^{1-\iota_w}}{\Pi_{t+1}}\right)^{-\epsilon_w(1+\varphi)}\left(\frac{\tilde{w}_{t+1}}{\tilde{w}_t}\right)^{\epsilon_w(1+\varphi)}\mathcal{F}_{t+1}^w, \tag{E.9}$$

$$\mathcal{J}_t^w = (\epsilon_w - 1)\Lambda_t \left(\tilde{w}_t\right)^{1-\epsilon_w} w_t \frac{N_t}{\Delta_t^w} + \beta \vartheta_w \mathbb{E}_t \left(\frac{\Pi_t^{\iota_w}\Pi^{1-\iota_w}}{\Pi_{t+1}}\right)^{1-\epsilon_w}\left(\frac{\tilde{w}_{t+1}}{\tilde{w}_t}\right)^{\epsilon_w - 1}\mathcal{J}_{t+1}^w, \tag{E.10}$$

$$\mathcal{J}_t^w = \mathcal{F}_t^w, \tag{E.11}$$

$$1 = \vartheta_w \left(\frac{\Pi_{t-1}^{\iota_w}\Pi^{1-\iota_w}}{\Pi_t}\frac{w_{t-1}}{w_t}\right)^{1-\epsilon_w} + (1 - \vartheta_w)\left(\tilde{w}_t\right)^{1-\epsilon_w}, \tag{E.12}$$

$$\Delta_t^w = (1 - \vartheta_w)\left(\tilde{w}_t\right)^{-\epsilon_W} + \vartheta_w \left(\frac{\Pi_t^{\iota_w}\Pi^{1-\iota_w}}{\Pi_{t+1}}\right)^{-\epsilon_w}\left(\frac{w_{t-1}}{w_t}\right)^{-\epsilon_w}\Delta_{t-1}^w, \tag{E.13}$$

$$\frac{\Pi_{w,t}}{\Pi_t} = \frac{w_t}{w_{t-1}}, \tag{E.14}$$

$$1 = \left\{\nu \left(p_t^B\right)^{1-\eta} + (1 - \nu)\left(p_t^G\right)^{1-\eta}\right\}^{\frac{1}{1-\eta}}, \tag{E.15}$$

$$\Delta_t^B Y_t^B = Z_t \left(1 - A_t^B\right)\left(N_t^B\right)^{1-\alpha_B}\left(K_{t-1}^B\right)^{\alpha_B}, \tag{E.16}$$

$$\Delta_t^G Y_t^G = Z_t \left(N_t^G\right)^{1-\alpha_G}\left(K_{t-1}^G\right)^{\alpha_G}, \tag{E.17}$$

$$mc_t^B = \frac{\left(1 - A^B\right)^{\frac{\zeta-1}{\zeta}} w_t N_t^B}{(1 - \gamma_B)(1 - \alpha_B) p_t^B Y_t^B}, \tag{E.18}$$

$$mc_t^B = \frac{\left(1 - A_t^B\right)^{\frac{\zeta-1}{\zeta}} r_{K,t}^j K_{t-1}^B}{(1 - \gamma_B)\alpha_B p_t^B Y_t^B}, \tag{E.19}$$

$$1 - \gamma_B = \left(1 - A_t^B\right)^{\frac{\zeta-1}{\zeta}}\left[1 - \gamma_B \left(\frac{p_t^B mc_t^B}{\tau \theta_t \mu_B}\right)^{\zeta-1}\right], \tag{E.20}$$

$$mc_t^G = \frac{w_t N_t^G}{p_t^G \left(1-\alpha_G\right) Y_t^G}, \tag{E.21}$$

$$mc_t^G = \frac{r_{K,t}^G K_{t-1}^G}{p_t^G \alpha_G Y_t^G}, \tag{E.22}$$

$$\xi_t = \mu_B Z_t \left[\frac{\left(1-A_t^B\right)^{\frac{\zeta-1}{\zeta}} - \left(1-\gamma_B\right)}{\gamma_B} \right]^{\frac{\zeta}{\zeta-1}} \left(N_t^B\right)^{1-\alpha_B} \left(K_{t-1}^B\right)^{\alpha_B}, \tag{E.23}$$

$$\mathcal{CO}_t = \left(1-\varpi\right) \mathcal{CO}_{t-1} + \xi_t + \xi^*, \tag{E.24}$$

$$Z_t = \left[1 - d_3 \left(d_0 + d_1 \mathcal{CO}_t + d_2 \mathcal{CO}_t^2\right)\right], \tag{E.25}$$

$$\mathcal{J}_t^B = \Lambda_t mc_t^B \frac{Y_t^B}{\Delta_t^B} + \beta \vartheta_B \mathbb{E}_t \left(\frac{\Pi_{t+1}^B}{\left(\Pi_t^B\right)^{\iota_B} \Pi^{1-\iota_B}} \right)^{\epsilon_B} \mathcal{J}_{t+1}^B, \tag{E.26}$$

$$\mathcal{F}_t^B = \Lambda_t \tilde{p}_t^B \frac{Y_t^B}{\Delta_t^B} + \beta \vartheta_B \mathbb{E}_t \left(\frac{\Pi_{t+1}^B}{\left(\Pi_t^B\right)^{\iota_B} \Pi^{1-\iota_B}} \right)^{\epsilon_B - 1} \frac{\tilde{p}_t^B}{\tilde{p}_{t+1}^B} \mathcal{F}_{t+1}^B, \tag{E.27}$$

$$\mathcal{J}_t^B = \frac{\epsilon_B - 1}{\epsilon_B} \mathcal{F}_t^B, \tag{E.28}$$

$$1 = \vartheta_B \left(\frac{\Pi_t^B}{\left(\Pi_{t-1}^B\right)^{\iota_B} \Pi^{1-\iota_B}} \right)^{\epsilon_B - 1} + \left(1-\vartheta_B\right) \left(\tilde{p}_t^B\right)^{1-\epsilon_B}, \tag{E.29}$$

$$\Delta_t^B = \left(1-\vartheta_B\right) \left(\tilde{p}_t^B\right)^{-\epsilon_B} + \vartheta_B \left(\frac{\Pi_t^B}{\left(\Pi_{t-1}^B\right)^{\iota_B} \Pi^{1-\iota_B}} \right)^{\epsilon_B} \Delta_{t-1}^B, \tag{E.30}$$

$$\Pi_t^B = \frac{p_t^B}{p_{t-1}^B} \Pi_t, \tag{E.31}$$

$$\mathcal{J}_t^G = \Lambda_t mc_t^G Y_t^G + \beta \vartheta_G \mathbb{E}_t \left(\frac{\Pi_{t+1}^G}{\left(\Pi_t^G\right)^{\iota_G} \Pi^{1-\iota_G}} \right)^{\epsilon_G} \mathcal{J}_{t+1}^G, \tag{E.32}$$

$$\mathcal{F}_t^G = \Lambda_t \tilde{p}_t^G Y_t^G + \beta \vartheta_G \mathbb{E}_t \left(\frac{\Pi_{t+1}^G}{\left(\Pi_t^G\right)^{\iota_G} \Pi^{1-\iota_G}} \right)^{\epsilon_G - 1} \frac{\tilde{p}_t^G}{\tilde{p}_{t+1}^G} \mathcal{F}_{t+1}^G, \tag{E.33}$$

$$\mathcal{J}_t^G = \frac{\epsilon_G - 1}{\epsilon_G} \mathcal{F}_t^G, \tag{E.34}$$

$$1 = \vartheta_G \left(\frac{\Pi_t^G}{\left(\Pi_{t-1}^G\right)^{\iota_G} \Pi^{1-\iota_G}} \right)^{\epsilon_G - 1} + \left(1-\vartheta_G\right) \left(\tilde{p}_t^G\right)^{1-\epsilon_G}, \tag{E.35}$$

$$\Delta_t^G = \left(1-\vartheta_G\right) \left(\tilde{p}_t^G\right)^{-\epsilon_G} + \vartheta_G \left(\frac{\Pi_t^G}{\left(\Pi_{t-1}^G\right)^{\iota_G} \Pi^{1-\iota_G}} \right)^{\epsilon_G} \Delta_{t-1}^G, \tag{E.36}$$

$$\Pi_t^G = \frac{p_t^G}{p_{t-1}^G} \Pi_t, \tag{E.37}$$

$$N_t = N_t^B + N_t^G, \tag{E.38}$$

$$I_t = \mathcal{I}_t^B + \mathcal{I}_t^G, \tag{E.39}$$

$$Y_t^G = (1-\nu)\left(p_t^G\right)^{-\eta}\left(C_t + \mathcal{G}_t + I_t\right), \tag{E.40}$$

$$Y_t^B = \nu\left(p_t^B\right)^{-\eta}\left(C_t + \mathcal{G}_t + I_t\right), \tag{E.41}$$

$$\frac{R_t}{R} = \left(\frac{R_{t-1}}{R}\right)^{r_r}\left[\left(\frac{\Pi_t}{\Pi}\right)^{r_\pi}\left(\frac{Y_t}{Y}\right)^{r_y}\right]^{1-r_r}\exp\left(\varepsilon_{rt}\right), \tag{E.42}$$

$$Y_t = p_t^B Y_t^B + p_t^G Y_t^G, \tag{E.43}$$

$$\log\left(\frac{\theta_t}{\theta}\right) = \varrho_\xi \log\left(\frac{\theta_{t-1}}{\theta}\right) + \varepsilon_{\xi t}, \quad \varepsilon_{\theta t} \sim N\left(0, \varsigma_\theta\right), \tag{E.44}$$

This system of equations solves for the following variables, Λ_t, C_t, $\mathcal{I}_t^B$, $\mathcal{I}_t^G$, I_t, Y_t^B, Y_t^G ,Y_t, Π_t, R_t, Q_t^B, Q_t^G, p_t^B, p_t^G, $\mathcal{J}_t^B$, $\mathcal{J}_t^G$, $\mathcal{J}_t^w$, $\mathcal{F}_t^B$, $\mathcal{F}_t^G$, $\mathcal{F}_t^w$, Δ_t^B, Δ_t^G, Δ_t^w, mc_t^B, mc_t^G, $\tilde{w}_t$, $\tilde{p}_t^B$, $\tilde{p}_t^G$, Π_t^B, Π_t^G,, Π_t^w, ξ_t, Z_t, $\mathcal{CO}_t$, A_t^B, N_t^B, N_t^G, N_t, K_t^B, K_t^G, w_t, ξ_t, $r_{K,t}^B$, $r_{K,t}^G$ and the shock process θ_t. Note in addition that there is a block including flexible price variables.

E.1 Steady State

The steady state is given by the following equations,

$$\Lambda_t = \left(\left(1-\phi\right)C\right)^{-\sigma}\left(1-\phi\beta\right), \tag{E.45}$$

$$R = \frac{1}{\beta}, \tag{E.46}$$

$$r_K^B = \frac{1}{\beta} - \left(1-\delta_K\right), \tag{E.47}$$

$$r_K^G = \frac{1}{\beta} - \left(1-\delta_K\right), \tag{E.48}$$

$$\mathcal{G} = \frac{\mathcal{G}}{Y}Y, \tag{E.49}$$

$$Q^B = 1, \tag{E.50}$$

$$Q^G = 1, \tag{E.51}$$

$$\mathcal{I}^B = \delta_K K^B, \tag{E.52}$$

$$\mathcal{I}^G = \delta_K K^G, \tag{E.53}$$

$$\tilde{w} = 1 \tag{E.54}$$

$$\tilde{p}^B = 1 \tag{E.55}$$

$$\tilde{p}^G = 1 \tag{E.56}$$

$$\Delta^w = 1, \tag{E.57}$$

$$\Delta^B = 1, \tag{E.58}$$

$$\Delta^G = 1, \tag{E.59}$$

$$\Pi^w = \Pi, \tag{E.60}$$

$$\Pi^B = \Pi, \tag{E.61}$$

$$\Pi^G = \Pi, \tag{E.62}$$

$$mc^B = \frac{\epsilon_B - 1}{\epsilon_B}, \tag{E.63}$$

$$mc^G = \frac{\epsilon_G - 1}{\epsilon_G}, \tag{E.64}$$

$$1 = \left\{\nu \left(p^B\right)^{1-\eta} + (1-\nu)\left(p^G\right)^{1-\eta}\right\}^{\frac{1}{1-\eta}}, \tag{E.65}$$

$$Y^B = Z\left(1 - A^B\right)\left(N^B\right)^{1-\alpha_B}\left(K^B\right)^{\alpha_B}, \tag{E.66}$$

$$Y^G = Z\left(N^G\right)^{1-\alpha_G}\left(K^G\right)^{\alpha_G}, \tag{E.67}$$

$$mc^B = \frac{\left(1 - A^B\right)^{\frac{\zeta-1}{\zeta}} wN^B}{(1-\gamma_B)(1-\alpha_B)\, p^B Y^B}, \tag{E.68}$$

$$mc^B = \frac{\left(1 - A^B\right)^{\frac{\zeta-1}{\zeta}} r_K^B K^B}{(1-\gamma_B)\,\alpha_B p^B Y^B}, \tag{E.69}$$

$$1 - \gamma_B = \left(1 - A^B\right)^{\frac{\zeta-1}{\zeta}}\left[1 - \gamma_B\left(\frac{p^B mc^B}{\tau\mu_B}\right)^{\zeta-1}\right], \tag{E.70}$$

$$mc^G = \frac{wN^G}{p^G(1-\alpha_G)\,Y^G}, \tag{E.71}$$

$$mc^G = \frac{r_K^G K^G}{p^G \alpha_G Y^G}, \tag{E.72}$$

$$\xi = \mu_B Z\left[\frac{\left(1 - A^B\right)^{\frac{\zeta-1}{\zeta}} - (1-\gamma_B)}{\gamma_B}\right]^{\frac{\zeta}{\zeta-1}}\left(N^B\right)^{1-\alpha_B}\left(K^B\right)^{\alpha_B}, \tag{E.73}$$

$$\mathcal{CO} = \frac{\xi + \xi^*}{(1-\varpi)}, \tag{E.74}$$

$$Z_t = \left[1 - d_3\left(d_0 + d_1\frac{\xi + \xi^*}{(1-\varpi)} + d_2\left(\frac{\xi + \xi^*}{(1-\varpi)}\right)^2\right)\right], \tag{E.75}$$

$$\mathcal{J}^w = \mathcal{F}^w, \tag{E.76}$$

$$\mathcal{F}^w = \frac{\epsilon_w \chi (N)^{1+\varphi}}{1 - \beta\vartheta_w}, \tag{E.77}$$

$$\mathcal{J}^w = \frac{(\epsilon_w - 1)\,\Lambda w N}{1 - \beta\vartheta_w}, \tag{E.78}$$

$$\mathcal{J}^G = \frac{\Lambda mc^G Y^G}{1 - \beta\vartheta_G}, \tag{E.79}$$

$$\mathcal{F}^G = \frac{\Lambda Y^G}{1 - \beta\vartheta_G}, \tag{E.80}$$

$$\mathcal{J}^G = \frac{\epsilon_G - 1}{\epsilon_G}\mathcal{F}^G, \tag{E.81}$$

$$\mathcal{J}_t^B = \frac{\Lambda mc^B Y^B}{1-\beta\vartheta_B}, \tag{E.82}$$

$$\mathcal{F}_t^B = \frac{\Lambda Y^G}{1-\beta\vartheta_B}, \tag{E.83}$$

$$\mathcal{J}^B = \frac{\epsilon_B - 1}{\epsilon_B}\mathcal{F}^B, \tag{E.84}$$

$$N = N^B + N^G, \tag{E.85}$$

$$I = \delta K^B + \delta K^B, \tag{E.86}$$

$$Y^B = \nu \left(p^B\right)^{-\eta}\left(C + \mathcal{G} + I\right), \tag{E.87}$$

$$Y^G = (1-\nu)\left(p^G\right)^{-\eta}\left(C + \mathcal{G} + I\right), \tag{E.88}$$

$$Y = p^B Y^B + p^G Y^G. \tag{E.89}$$