The Macroeconomic Implications of Carbon Pricing Announcements: Evidence from the EU ETS

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Abstract

This paper studies the effect of carbon pricing shocks on the macroeconomy using a high-frequency identification approach. Focusing on the European carbon market, I consider whether carbon policy announcements can be summarised by a single factor, or whether there are additional dimensions that need to be accounted for. By measuring the high-frequency surprise changes of a spectrum of EUA carbon futures around 145 regulatory events, I find that the events can be summarised by two factors rather than just a single factor. A particular rotation of the orthogonal instruments is used to derive two novel instruments, namely, an "action" instrument, which captures changes to the current carbon policy rate, and an "expected path" instrument, which captures changes to the expectations about future carbon policy. I measure the effects of the two factors on a class of asset prices by estimating a daily local-projection model. This is complemented by estimating a Bayesian external instruments VAR model to map out the dynamic macroeconomic effects. I document that a tighter carbon policy successfully reduces emissions, although this is simultaneously met with significantly lower economic activity and higher prices that are persistent over the horizons. More importantly, the results indicate that the "expected path" instrument dominates in its negative implications on macroeconomic aggregates, stressing the importance of capturing the additional dimension of carbon policy announcements, particularly from a policy perspective.

JEL Classification: E31, E32, H23, Q43, Q54.

Key Words: Carbon pricing, cap-and-trade, EU ETS announcements, high-frequency identification, external instruments

1 Introduction

Climate change is one of the most important global issues that has gripped the attention of policymakers over recent years. In line with the goals of the Paris Agreement, policymakers have intensified their efforts to implement measures such as carbon taxes and cap-and-trade systems to address both the environmental and economic impacts of climate change. While the physical effects of climate transition policies have proven effective in reducing emissions, the economic implications of such decarbonization initiatives remain ambiguous at large. More importantly, there is limited understanding of how expectations regarding the future direction of carbon policy influence the broader economy.

To address these policy-relevant questions, I utilise a high-frequency identification approach in the context of the European Union Emission Trading System (EU ETS) carbon market. This method effectively addresses the issue of endogeneity in carbon pricing by measuring the daily surprise changes of a spectrum of EUA carbon futures within a daily window following EU ETS regulatory events, allowing us to isolate exogenous events. Formally, I use the fact that the EU ETS regularly publishes updates about the supply of carbon, which can significantly impact the price of emission allowances. This creates an ideal setting for applying a high-frequency identification approach. To analyse this, I collect 145 regulatory news events from 2005 to 2023 that summarise information about the supply of emission allowances. To this end, I construct a series of carbon policy surprises around the EU ETS regulatory events.

The main contribution of the paper is to shed light on the role of the EU ETS regulatory events but, more importantly, to examine whether the EU ETS regulatory events can be summarised by a single factor, which is captured by the surprise component of the change in the current carbon futures target or whether it encapsulates additional information about the future path of policy which may be relevant in affecting the macroeconomy. I motivate that the complexity of the EU ETS regulatory events encourages us to explore this additional dimension of carbon pricing announcements. To do this, I extend the study by Känzig (2023), which only considers a single asset, that is, the changes in the current-month carbon futures to the regulatory events. The main point of departure in this paper is that rather than using the current-month futures changes directly as an external instrument, I consider the surprise changes of a spectrum of EUA carbon futures, including the current-month, 3-, 6-, 9-, 12- month, 2- and 3-year rates.

From a methodological perspective, I use the principal components (PCs) of the estimated high-frequency changes of carbon futures as a basis to construct orthogonal instruments for the carbon policy shocks. The results suggest that the EU ETS can be summarised along two dimensions rather than just one. Subsequently, I apply a rotation to the subset of the PCs to yield two novel measures of carbon policy shocks. The advantage of this rotation is that we can attach a structural interpretation to the factors whilst ensuring that the components are still orthogonal. This enables us to separate information about the current rate from information about the expected path of future policy.

As a result, the first component can be summarised as an "action" instrument, which captures changes to the current policy rate, and the second component can be summarised as an "expected path" instrument, which captures changes to the expectations about future policy and is restricted not to affect the current-month short rate. Differentiating between the two instruments is crucial for the carbon market. It is useful to the extent that by attaching a structural interpretation to both factors, we can examine their separate transmissions to the macroeconomy.

To do this, I estimate a daily local projection to examine the persistence of the carbon policy shocks over the sample on a class of asset prices. To capture the economic implications, the structural components are used in an external instruments (Bayesian) VAR model using monthly data from January 1999 to December 2021 to map out their dynamic macroeconomic effects.

The estimated impulse responses have important economic and policy implications. More importantly, it highlights the distinct transmission mechanisms of the two instruments to the macroeconomy. A carbon policy shock identified by the action instrument that is normalised to increase energy prices by 1 per cent contributes to declining emissions, reaching the minimum after two years, suggesting that the carbon policy shocks effectively reduce emissions. However, this is followed by a series of economic costs, including higher energy and headline consumer prices and lower economic activity, where variables such as industrial production, unemployment rate, and stock prices all respond in a contractionary manner, reaching the minimum after two years.

More importantly, the results highlight that the carbon policy shock identified by the expected path instrument, also normalised to increase energy prices by 1 per cent, contributes to even larger negative effects on economic activity, which materialises after one year. For instance, industrial production declines to its minimum after one year by 0.62 per cent relative to the modest decline of 0.34 per cent two years following the action instrument shock. The results, therefore, suggest that the expected path instrument has stronger negative demand effects, likely a result of producers adjusting their production in anticipation of tighter future carbon policy. The impulse responses of other macroeconomic aggregates confirm these findings.

The larger negative responses of economic activity following a carbon policy shock identified by the expected path instrument are further explored and confirmed when examining the wider propagations and the transmission channels at play. By including measures that capture monetary policy, real exchange rates, and the terms of trade, the results highlight that monetary policy reacts to higher prices in a contractionary manner. Considering the effect on production, employment, and inflation expectations, we find that the shock contributes to lower expectations, reaching a minimum after two years, reflecting the decline of industrial production reported in the baseline estimates. To better examine the role of carbon policy shocks on prices, I also consider the sub-indices of prices, including durables, non-durables, services, and core consumer prices, and find that the transmission of the two shocks is consistent with the baseline results, suggesting that the carbon policy shock contributes to higher prices. However, the action instrument contributes to relatively higher prices for all sub-indices.

To better highlight the discrepancies between the two instruments, I conduct historical decomposition and variance decomposition exercises on the baseline variables. The results highlight key differences where the carbon policy shock identified by the action instrument explains a larger proportion of the variation of the variables, especially headline consumer prices. On the other hand, the historical decomposition highlights key differences in the contribution of the two shocks, where the historical variation of emissions and energy prices are largely explained by the action instrument and depend on the nature of the economy. Overall, the results suggest that accounting for both dimensions of the EU ETS carbon market is crucial in establishing their transmission on the macroeconomy.

2 Related literature and contribution

The paper aims to contribute to the growing literature on climate transition policies by combining high-frequency identification with the EU ETS carbon market. While an extensive number of papers have considered the effectiveness of carbon tax policies and their transmission to the macroeconomy, little is known regarding the economic implications of cap-and-trade systems. Having said that, the vast majority of the literature has documented the effectiveness of carbon taxes in reducing emissions (see, e.g. Metcalf & Stock (2020); Murray & Rivers (2015); Rafaty et al. (2020)), but project mixed findings regarding the economic implications of carbon taxation. For instance, simulations from general equilibrium models find that carbon taxes are contractionary (McKibben et al. (2017)) whereas more recent empirical evidence finds that while carbon taxes lower GDP growth and employment, the impact is not as profound (Metcalf (2019); Metcalf & Stock (2020); Bernard & Kichian (2021); Känzig & Konradt (2023). This finding is consistent across studies that consider carbon taxes in the Canadian province of British Columbia (Bernard et al. (2018); Metcalf (2019); Bernard & Kichian (2021)) as well as in European countries (Metcalf & Stock (2020)).

Several studies have also examined the role of carbon taxes in generating inflationary pressures. For instance, focusing on a set of 18 carbon taxes in both Europe and Canada, Konradt & di Mauro (2021) does not find evidence of aggregate inflationary pressures. Similarly, Metcalf (2019) finds that while carbon taxes do not contribute to inflationary pressures, it does increase the cost of energy. Considering the Euro area, Konradt et al. (2024) reach a similar conclusion and find that carbon taxes increase the cost of energy but do not contribute to higher inflation. To justify these results, there is consensus suggesting that the negative implications of carbon taxes depend on whether countries recycle their revenues and whether they operate through an independent central banking system that can separately respond to inflationary pressures. These countries are relatively more insulated from the negative effects of carbon taxes and do not face high inflationary pressures (Konradt & di Mauro 2021).

Given the mixed findings regarding the implications of carbon taxation, the literature has otherwise documented sizeable economic effects of carbon pricing, both on emissions (see e.g. Martin et al. (2014); Andersson (2019)), economic activity (Känzig & Konradt (2023)), and stock prices (see e.g. Känzig (2023); Hengge et al. (2023)). Several studies have documented the heterogeneous inflationary effects of carbon pricing shocks. For instance, Benmir & Roman (2022) highlights that carbon pricing shocks increase the price of energy and have significantly negative effects on the economy when considering the California cap-and-trade market. Similarly, Moessner (2022) finds that for 35 OECD countries from 1995 to 2020, an increase in the price of ETS increases energy and headline CPI inflation but reports limited effects on core inflation. This contrasts the finding by Nishigaki (2023), who estimates an SVAR model and reports that a shock to EUA prices contributes to higher long-run inflation expectations and core inflation when accounting for the role of renewable energy investment.

Given the mixed findings relating to the economic effects of carbon pricing shocks, this paper aims to provide robust evidence on the transmission of carbon policy shocks. Aside from that, the main scope of the paper is to derive novel instruments for carbon policy shocks that not only focus on changes in the current stance of carbon policy but also relate to the expectations of future carbon policy. From a methodological perspective, this study relates to the high-frequency approach of identifying shocks, which has mainly been studied in the context of monetary policy. A large literature has focused on measuring the change in high-frequency asset prices in a tight window around FOMC announcements (see e.g. Kuttner (2001); Rigobon & Sack (2004); Ellingsen & Söderström (2004); Beechey & Österholm (2007); Nakamura & Steinsson (2018)). However, most of these studies have focused on a single monetary policy shock by capturing the unexpected changes in the current policy rate. Given the complexity of FOMC announcements, several studies have expanded the single-shock approach to identifying two shocks. They have considered using the measures as external instruments in a VAR to assess their macroeconomic effects (Gertler & Karadi 2015)). Differently to the single-shock analysis, the shocks are identified from high-frequency changes of a spectrum of federal funds rates futures for maturities up to a year (Gürkaynak et al. (2005); Mumtaz et al. (2023)), and maturities up to 10-years (see e.g. Kaminska et al. (2021)).

The high-frequency identification approach has been applied in several contexts beyond the monetary policy setting. For instance, studies have used high-frequency changes around OPEC announcements in the context of the oil market (Demirer & Kutan (2010); Känzig (2021)) as well as high-frequency changes around EU ETS regulatory events in the context of the carbon market (Fan et al. (2017); Känzig (2023)). I aim to contribute to the literature by extending the single-shock analysis in the context of the carbon market into two shocks to capture additional dimensions relating to the expectations of future carbon policy. I rely on the high-frequency variation of a spectrum of carbon futures out to a horizon of three years. From a methodological perspective, this paper extends the work by Känzig (2023), which identifies a carbon policy shock by measuring the change in the current-month carbon futures around EU ETS regulatory events. The main point of departure is that rather than using the current-month futures changes directly as an external instrument, I apply a rotation to the carbon futures reactions to derive two novel measures of carbon policy shocks, which can be independently categorised as "action" instrument and an "expected path" instrument. The advantage of this approach is that we can attach a structural interpretation to the factors, which enables us to separate information about the current rate from information regarding the expected path of future policy. I show that these differences are important to capture because by also considering the role of expectations for the future path of carbon policy, we can examine the importance of communication in the context of the carbon market and examine whether EU ETS regulatory events include additional dimensions that are not only captured and summarised by single-factor shocks.

The remainder of the paper proceeds as follows. Section 3 provides details of the EU ETS carbon market and introduces the high-frequency dataset as well as the construction of the factors. Section 4 provides details on the estimation of a daily local projection model to estimate the impact of carbon policy shocks on asset prices. Section 5 provides an overview of the estimation method. Section 6 reviews the baseline results of the external instrument VAR model. Section 7 provides the estimates from the wider set of transmission channels, and finally, Section 8 concludes the paper.

3 High-frequency data

In this section, I provide some background information on the carbon futures market in the European Union and provide details on the method taken to construct the carbon policy shocks that will be used in the estimation.

3.1 The European carbon market

Following the 1997 Kyoto Protocol, the EU has committed to implementing carbon policies to meet emission reduction targets. With that, the European emissions trading system was established in 2005 as a key driver for decarbonisation. Being the largest carbon market in the world, it accounts for around 40 per cent of the EU's greenhouse gas emissions. The carbon market operates under a cap-and-trade system, implying that an overall cap is set on how much certain greenhouse gas emissions can be emitted. Each year, the cap is reduced to reach the objectives of the EU ETS, which is to limit greenhouse gas emissions from power stations and other energy-intensive industries by a certain percentage every year.

The carbon market operates by giving companies the right to emit one tonne of C02 within a calendar year. In essence, the system requires companies to report emissions where such emission allowances can be traded across companies. In particular, companies can buy an increasing proportion of allowances through auctions on the EU carbon market but can also receive allowances for free. Alternatively, companies can also use limited international credits from emission-saving projects. Companies that reduce their emissions can use their spare allowances for future needs or sell them to other companies that have limited allowances. Alternatively, companies that do not reduce their emissions risk paying heavy fines and must surrender allowances to cover their emissions (Comission (2020a)).

The EU ETS operates in trading phases, with each phase undergoing several revisions to help reach EU climate targets. While the system is currently in the fourth trading phase (2021-2030), Figure 1 presents the evolution of EUA carbon price across the different phases from 2005 to 2023. [1] The first phase was the pilot phase, lasting for three years, from 2005 to 2007. Having successfully established a price for carbon, most of the allowances were freely allocated to companies in this first stage. Moreover, the pilot phase relied on estimates of annual emissions data, leading to imprecise caps being set in phase one. The significant carbon price decline in 2006 resulted from

[1]The carbon price is measured by the price of the current-month carbon futures contract over the different phases of the EU ETS.

Figure 1: The EU Carbon Price

the total amount of allowances exceeding the total number of emissions, eventually resulting in the price converging to zero since phase one allowances were not transferred to phase two.

The second phase lasted from 2008 to 2012 and coincided with the first commitment period of the Kyoto Protocol, which was associated with several countries meeting emission reduction targets. Contrary to the first phase, several changes were implemented. For instance, the proportion of free allocation fell to around 90 per cent, businesses were allowed to buy international credits, several countries held auctions, and the EU ETS expanded its covered sectors, including the aviation sector, in 2012. Furthermore, relative to the first phase, reliable emissions data became available, resulting in the cap on allowances being lowered to raise the price of carbon. Having said that, the moderate increment of carbon prices during the second phase was a consequence of economic inactivity caused by the 2008 economic crisis, which led to falling emissions and a surplus of allowances and credits.

The third phase, which took place from 2013 until the end of 2020, was characterised by significant changes in its regulations relative to the first two phases. In particular, caps that were set at the national level were replaced by a single EU-wide cap on emissions. Moreover, instead of free allocation, auctioning became the default form for allocating allowances. The system further expanded by including more sectors and gases such as nitrous oxide, perfluorocarbons, and carbon dioxide. Given the surplus of allowances that built up following the Great Recession, in

2014, the Commission postponed the auctioning of 900 million emission allowances. To further reduce the current surplus of allowances as well as insulate the system from major shocks, the Commission introduced a market stability reserve in January 2019. As a result, back-loaded and unallocated allowances were not auctioned in the final years of phase three but were transferred to the reserve instead.

The fourth and current phase, which began in 2021 and is set to run until 2030, was characterised by further action taken by the Commission to reduce allowances and achieve the EU's 2030 emission reduction targets. In particular, the pace of annual reductions in total allowances increased to 2.2 per cent from the previous 1.74 per cent. Continuing the need to insulate the system from future shocks, the market stability reserve was reinforced. In addition, the Commission further revised and expanded the scope of the EU ETS to achieve a climate-neutral EU by 2050 (Comission 2020a).

3.2 Construction of the carbon policy surprises

The EU ETS provides a suitable ground to investigate the role of carbon policies on the macroeconomy. Particularly, with regular updates made by the EU ETS in enforcing lower emissions, I utilise the regulatory events to construct the carbon policy surprise series. Encouraged by the event study literature on FOMC announcements in the context of monetary policy (see, e.g. Gürkaynak et al. (2005); Gertler & Karadi (2015)), I collect a comprehensive list of regulatory events that relate to the EU ETS. These events can include either a decision made by the European Commission, a vote of the European Parliament, or a judgement from a European court. This information is included in the official journal of both the European Union and the European Commission Climate Action news archive. Similar in spirit to Känzig (2023), I focus on regulatory news regarding the overall supply of emission allowances to allow for comparability. To this end, I include events that concern the overall cap in the EU ETS, the free allocation of allowances, the auctioning of allowances, and the use of international credits. I extend the sample and identify a total of 145 regulatory events from 2005 to 2023.

The carbon market is suitable for measuring high-frequency changes in EUA carbon futures since emission allowances can be auctioned off and traded in different markets since there exists a spot and futures market in which the EUAs can be traded. Formally, EUAs define the right to emit one tonne of carbon dioxide equivalent gas and can be traded across different markets. The spot markets include Bluenext in Paris, EEX in Leipzig, and Nord Pool in Oslo. Alternatively, EUA futures can be traded in futures markets, including EEX in Leipzig and ICE in London. In this paper, I collect daily carbon futures data from the ICE since it dominates the price discovery process in the European carbon market (Stefan & Wellenreuther 2020).

Considering the event study literature, the maturity of the carbon futures contract is a crucial choice in the identification. Since in this paper I aim to capture both the current and the expected path of regulatory events on the macroeconomy, I select the longest maturities available including the current-month carbon futures rate out to the three-year carbon futures rate. Hence, I obtain data for the current, 3-, 6-, 9-, 12-month, 2-, and 3-year EUA carbon futures. The high-frequency (daily) data on EUA carbon futures prices are sourced from Refinitiv.

3.3 High-frequency identification

The aim of this paper is to construct a time series of carbon policy surprises by utilising the surprise changes of a spectrum of carbon futures prices around regulatory events. The EU ETS carbon market provides a suitable setting for utilising the high-frequency identification approach to identify carbon policy shocks given that regulatory events can have significant effects on the price of emission allowances.

Furthermore, the high-frequency identification approach is useful as it directly addresses the potential endogeneity concerns related to the carbon market. In particular, by measuring the changes in the carbon futures within a tight window around the regulatory event, I isolate the impact of the ET ETS's regulatory events and ensure that the corresponding instrument is exogenous and appropriately captures unexpected changes in carbon prices. As a result, reverse causality of economic conditions can be ruled out because they are already taken into consideration by the market before the regulatory event and are unlikely to change within a sufficiently tight window. This ensures that the derived series will only capture changes in the carbon futures that are driven by the EU ETS regulatory news.

Regarding the size of the event window, I select a daily window for several reasons. First, it ensures that no other background noise influences the response (Nakamura & Steinsson 2018). Moreover, a daily window is suitable in this framework as it gives the markets enough time to respond to regulatory news whilst ensuring that the window is narrow enough to exclude other data releases that can move carbon prices. Alternatively, using an intra-day window is unsuitable in the context of the carbon market since the release times of the policy events are not always available over the sample period.

Based on 145 regulatory news, I construct the carbon policy surprise series by measuring the percentage change in the EUA futures price on the day of the EU ETS regulatory event relative to the price on the last trading day before the event:

$$CPSurprise^h_{t,d} = F^h_{t,d} - F^h_{t,d-1} \tag{1}$$

where d and t denote the day and the month of the event, respectively and $F_{t,d}$ is the (log) settlement price of the EUA futures contract in month t on day d.

For the estimation, the daily surprises $CPSurprise^h_{t,d}$ are aggregated to a monthly series $CPSurprise^h_t$ by summing over the daily surprises in a given month. Alternatively, in months with no regulatory events, the monthly series takes the value of zero. Aggregating the daily surprises in a monthly frequency is necessary, given that the macroeconomic variables that are considered in the estimation are available at a monthly frequency.

3.4 Diagnostics of the surprise series

In this section, I analyse the high-frequency reactions of EUA carbon futures at different maturities using a daily window around EU-ETS regulatory events. As mentioned previously, in this paper, I examine the role of expectations in the carbon market. To do this, I not only consider the changes to the current-month carbon futures, but I also measure the changes to a spectrum of carbon futures out to a horizon of three years. Therefore, I capture daily changes across seven different EUA carbon futures maturities to construct the carbon surprise series.

To better characterise the dynamics of the EUA carbon futures at different maturities, I present the reactions of carbon futures around the regulatory events across the seven maturities in Figure 2. The figure highlights the differences in the reactions of the carbon futures to EU ETS regulatory events across the different phases. In the second phase, the reactions across all maturities were somewhat consistent in their responses to regulatory events. However, this consistency is not persistent, given that the largest discrepancies across the maturities were observed in the third phase, particularly between 2012 and 2015.

The third phase was marked by the largest fluctuations in reactions for all maturities across the sample, which is not surprising given that this phase coincided with significant changes in regulatory events in the carbon market. For example, in April 2013, following the European Parliament's vote against the Commission's back-loading proposal, all carbon futures from the current month up to the one-year maturity experienced a significant decline. Notably, this decrease

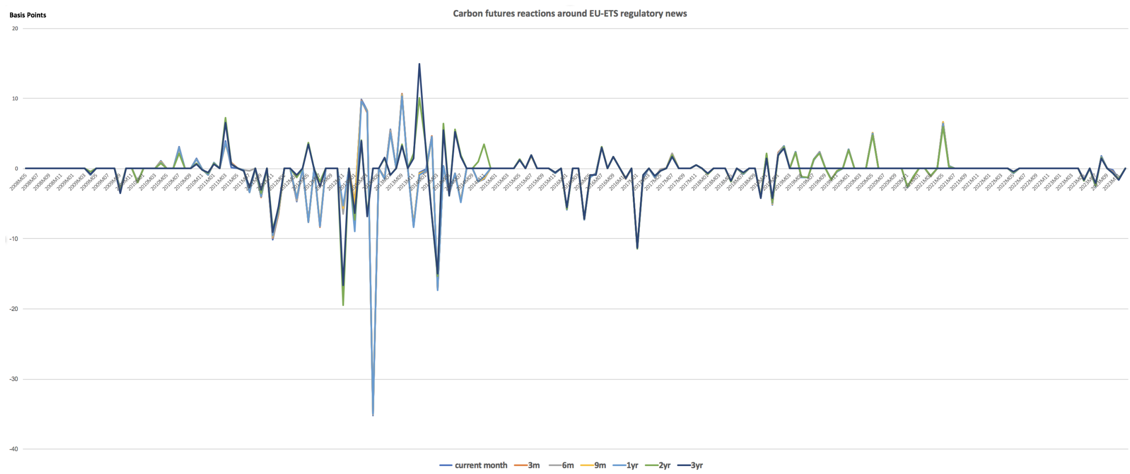

Figure 2: Carbon futures changes around EU ETS regulatory events across maturities

was not mirrored by a similar drop in the carbon futures at the two- and three-year maturities. My findings indicate that shorter maturities consistently reacted to the regulatory events, while the three-year rate displayed distinct responses. This distinct behaviour was especially evident in the fourth phase, from 2020 to 2022, during which the three-year rate did not respond to regulatory events at all.

The differences in reactions across various maturities are more clearly illustrated in Table 1, which presents the basic statistics for these series. Key observations indicate that the average responses were negative across all maturities, with the 2-year and 3-year responses showing the smallest average values. Conversely, the current-month future rate exhibited the largest negative average. Additionally, the current-month carbon future rate had the highest standard deviation compared to the longer maturities, indicating that it is the most volatile in response to regulatory events over the sample period. In contrast, the 2-year and 3-year carbon futures showed the least volatility, suggesting that these longer maturities are less sensitive to regulatory changes.

3.5 Construction of the carbon factors

Recall that the main contribution of this paper is to analyse whether communication about the future supply of carbon can be captured by a single factor, more specifically, the surprise component of the change in the current carbon futures or whether there are additional dimensions that need to be incorporated. Therefore, to summarise the dimensions of carbon policy, I examine the number of factors needed to summarise EU ETS regulatory events using a method similar in spirit to Gürkaynak et al. (2005).

Table 1: Effect of EU ETS regulatory events on carbon futures across different maturities

	Current-month	3-month	6-month	9-month	1-year	2-year	3-year
Average response, bps	-0.50	-0.29	-0.30	-0.36	-0.37	-0.17	-0.21
St. Deviation	3.85	3.18	3.20	3.03	3.06	2.34	2.21
Minimum, bps	-35.26	-35.10	-35.08	-34.98	-34.96	-19.52	-16.59
Maximum, bps	10.71	10.64	10.57	10.43	10.35	10.06	14.91

The matrix X can be denoted as a T x n matrix with rows corresponding to the EU ETS regulatory events and columns corresponding to EUA carbon futures. Each element of X denotes the change in the respective carbon futures price in a narrow window around the EU ETS regulatory event. We can express X as follows:

$$X = F\Lambda + \eta \tag{2}$$

where F is a T x k matrix of unobserved factors (where $k < n$), Λ is a k x n factor loading matrix, η is a T x n matrix of white noise disturbances. In this case, X is a matrix that contains 145 rows corresponding to the number of EU ETS regulatory events and 7 columns corresponding to the current, 3-, 6-, 9-, 12-month, 2-, and 3-year EUA carbon futures. In this setting, we are interested in assessing the number of factors (columns of F) required to summarise matrix X.

To estimate the unobserved factor matrix F, I utilise the principal components method and apply it to the data matrix X. The instruments for the carbon policy shocks are obtained by decomposing the high-frequency changes of EUA futures into principal components (PCs) and selecting the most important PCs. Using the set of EUA carbon futures (current, 3m, 6m, 9m, 12m, 1y, 2y, and 3y) that characterise the expected path of EUA futures over the 3 years, the data suggests that the first two PCs account for 94.4 per cent of the total variance across the maturities, with their contributions amounting to 83.7 per cent and 10.7 per cent, respectively. Based on the PCA analysis, two orthogonal instruments are extracted, denoted as F_1 and F_2. It is worth noting that the two respective factors expressed in this form are orthogonal but do not yet have a structural interpretation, making it difficult to isolate their role in their transmission. Subsequently, there is a risk that both factors may be correlated with surprises in the current month's carbon futures target. This is important to distinguish because the objective of the paper is to develop a separate instrument that relates to the expected path component while ensuring it does not impact the current month's short rate.

To facilitate the interpretation of the factors, I perform a rotation of the two factors following Gürkaynak et al. (2005) to yield two new factors, which can be denoted as Z_1 and Z_2. The benefit is that the two rotated factors have a structural interpretation but remain orthogonal and still explain the same proportion of the matrix X as F_1 and F_2. The crucial difference is in the interpretation of the factors. In essence, the unexpected change in the current target carbon futures rate is exclusively driven by the Z_1, which denotes the first column of Z. As a result, the first component can be characterised as the "target" factor, which can be interpreted as a surprise in "action". More specifically, the factor captures news about the direction of short-term carbon policy which in this case is policy in the current month.

It is worth noting that the “target” factor is close in principle to the carbon policy shock by Känzig (2023). The main point of departure is that the "target" factor strictly captures the component that relates to the current-month carbon futures rate, whereas the measure by Känzig (2023) relies on raw changes in current-month carbon futures data, which may contain elements of both dimensions, hence, capturing the net-effect. Alternatively, in this paper, I separate these two dimensions since the factor estimation strips out white noise from the data. Therefore, it can be assumed that the target factor (Z_1) is a better measure of the component of the carbon futures rate surprises relative to the standard measure that is based on the raw data of the current-month carbon futures rate (Gürkaynak et al. 2005).

The second component can be characterised as the “path” factor, which can be interpreted as a surprise in the "expected path", which captures changes in future carbon rates out to a horizon of three years and is independent of changes in the short-term carbon futures. Thus, the second column of Z, denoted by Z_2, captures the remaining dimensions which summarise the EU ETS regulatory events which change futures rates for the subsequent three years without changing the current carbon futures rate. Under this assumption, it is useful to suggest that the expected path captures an additional transmission that focuses on the surprises of regulatory events that impact expectations about future rates that are independent of the current stance.

To better illustrate the rotation of the factors, we can express Z as a 145 x 2 matrix, which has the following representation:

$$Z = FU \tag{3}$$

where U is defined as a 2 x 2 orthogonal matrix:

$$U = \begin{bmatrix} \alpha_1 & \beta_1 \\ \alpha_2 & \beta_2 \end{bmatrix} \tag{4}$$

and is uniquely identified by the following four restrictions. First, the columns of U are normalised to have unit length, which normalises Z_1, and Z_2 to have unit variance. Secondly, the new factors Z_1 and Z_2 should be orthogonal to each other such that:

$$E(Z_1 Z_2) = \alpha_1 \beta_1 + \alpha_2 \beta_2 = 0 \tag{5}$$

Third, Z_2, which denotes the second column of Z is a vector that does not influence the current futures contract. In particular, let γ_1 and γ_2 denote the (known) loadings of the current-month carbon futures contract on F_1 and F_2 (the unrotated factors form the PCA), respectively. Since

$$F_1 = \frac{1}{\alpha_1\beta_2 - \alpha_2\beta_1}[\beta_2 Z_1 - \alpha_2 Z_2] \tag{6}$$

$$F_2 = \frac{1}{\alpha_1\beta_2 - \alpha_2\beta_1}[\alpha_1 Z_2 - \beta_1 Z_1] \tag{7}$$

It follows that:

$$\gamma_2\alpha_1 - \gamma_1\alpha_2 = 0 \tag{8}$$

The unique matrix U can be solved given the set of conditions are satisfied.

To solidify the interpretation of the factors, Table 2 reports the loadings on the seven maturities in the high-frequency dataset on the two instruments. The structural interpretation of the factors following the rotation ensures that only the first component of the PCs affects the current-month future rate, whereas the second component does not. This is highlighted by the first element in the second column being equal to zero. More importantly, we find that the patterns of the loadings across maturities differ across the two instruments. “Action” has a fluctuating pattern over the maturities, at least for the shorter maturities, with the peak occurring at the 3-month rate. Having said that, the loadings display a declining pattern at longer maturities, with the 3-year maturity displaying the smallest value, suggesting that the importance of the action factor is declining with maturity. In contrast, the “expected path” has an increasing pattern with the 3-year maturity displaying the largest value.

Table 2: Loadings on the components of carbon policy surprises

Rotated PCs	Current-month	3-month	6-month	9-month	1-year	2-year	3-year
"Action"	0.918	0.983	0.977	0.979	0.977	0.384	0.328
"Expected path"	0	0.028	0.020	0.044	0.055	0.904	0.926

3.6 The target and path factor

In this section, I present the dynamics of the factors over the sample period, as illustrated in Figure 3. Both the target and path factor series exhibit a relatively consistent pattern throughout the sample. However, the most significant fluctuations occurred during the first half of the sample, particularly towards the end of the second phase and the beginning of the third phase, from 2012 to 2014. This increased volatility is understandable, as major regulatory events during this period played a crucial role in shaping the carbon market.

For example, in March 2011, both factors responded positively when the Commission proposed to auction 120 million allowances in 2012. The significant positive change in the path factor aligns with the idea that this regulatory event was more indicative of the future policy trajectory. In contrast, in November 2012, the path factor experienced a substantial negative surprise change following a regulatory update regarding the Commission's amendment to back-load 900 million allowances to 2019-2020. Since this amendment also indicated future policy directions, the target factor did not respond with an equally large negative surprise change.

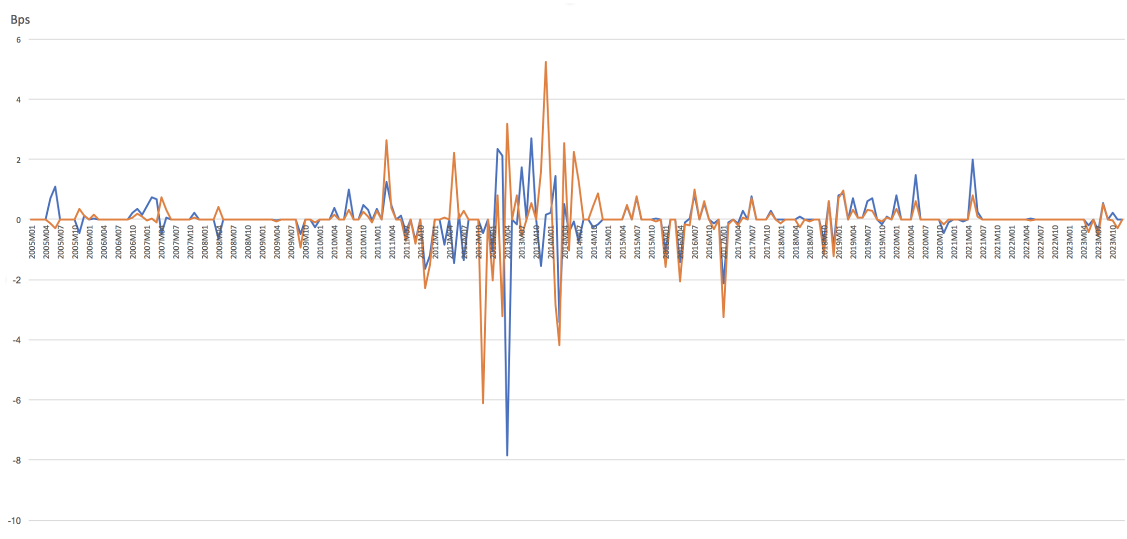

Figure 3: The target and path factor

In April 2013, the European Parliament voted against the Commission's back-loading proposal, which resulted in the largest negative surprise change for the target factor. This regulatory event primarily revealed information about immediate carbon policy decisions rather than providing clarity on the future direction of carbon policy. As a result, it did not lead to a similarly significant surprise change in the path factor.

Conversely, in September 2013, the Commission finalized the free allocation for the industrial sector in phase three. This decision generated a positive surprise change for both the target and path factors. However, the target factor saw a significantly larger increase because the event was more directly related to current policy changes.

In certain cases, we find that the discrepancies between the two factors are not only related to the magnitude of the surprises but also to the responses elicited by these surprises. For instance, the Commission's temporary approval of free allowances for power plants led to a negative surprise change in the target factor in May 2012. However, this was not mirrored by a negative surprise change in the path factor, as the Commission had earlier published guidelines for setting national limits for 2013-2020 during the same month. Given that this event signalled potential future increases in carbon prices, the path factor actually experienced an upward shift.

In our analysis, we observed that the largest discrepancies between the two factors occurred during the first two phases and at the beginning of the third phase, specifically up until the end of 2014. However, over the course of the sample period, these discrepancies diminished. By the end of the third phase, we noted that both factors showed relatively similar responses to regulatory events. For example, in February 2019, the introduction of a stricter carbon leakage list resulted in both the target and path factors increasing by the same amount.

In the fourth phase, the volatility of the factors was significantly lower compared to the first half of the sample. This can be attributed to the fact that most substantial regulatory changes took place during the second and third phases. Given the observed differences in the dynamics between the two factors, we plan to estimate the impact of the identified carbon policy shocks separately using an external instrument VAR approach. The next section will detail the estimation procedure.

4 Asset price responses to carbon policy shocks

4.1 Daily local projections

One of the contributions of this paper is to highlight the role of the target and the path factor on a class of asset prices. By estimating a daily local projection, I examine whether the effect of carbon policy shocks are persistent over the sample. Using daily financial data, I collect data on the 3-month, 1-year, 2-year, and 10-year Overnight Index Swaps (OIS) rates and stock market volatility in the EU from 2005 to 2023.

I estimate the following local projections similar to Jarociński (2024):

$$x_{t+h} - x_{t-1} = \alpha + \beta_h^i u_{i,t} + e_t \tag{9}$$

where x_t is a daily financial variable, and t represents the day in which there is an EU ETS regulatory event. To consider the degree of persistence of the shock on the financial variables, I include (business days) horizons of $h = 1, 2, 3, 4, 5, 10, 15, 20, 25$. $u_{i,t}$, $i = 1, 2$ are one sample standard deviation shocks relating to the target and the path factor, respectively. It is worth noting that the one standard deviation shocks based on the local projections are included in the regression individually where $\beta_h^i u_{i,t}$ captures the effect of a one-sample standard deviation shock. The equation is estimated via OLS with heteroskedasticity-robust errors. A bootstrap procedure accounts for the uncertainty in the estimation of the shocks.

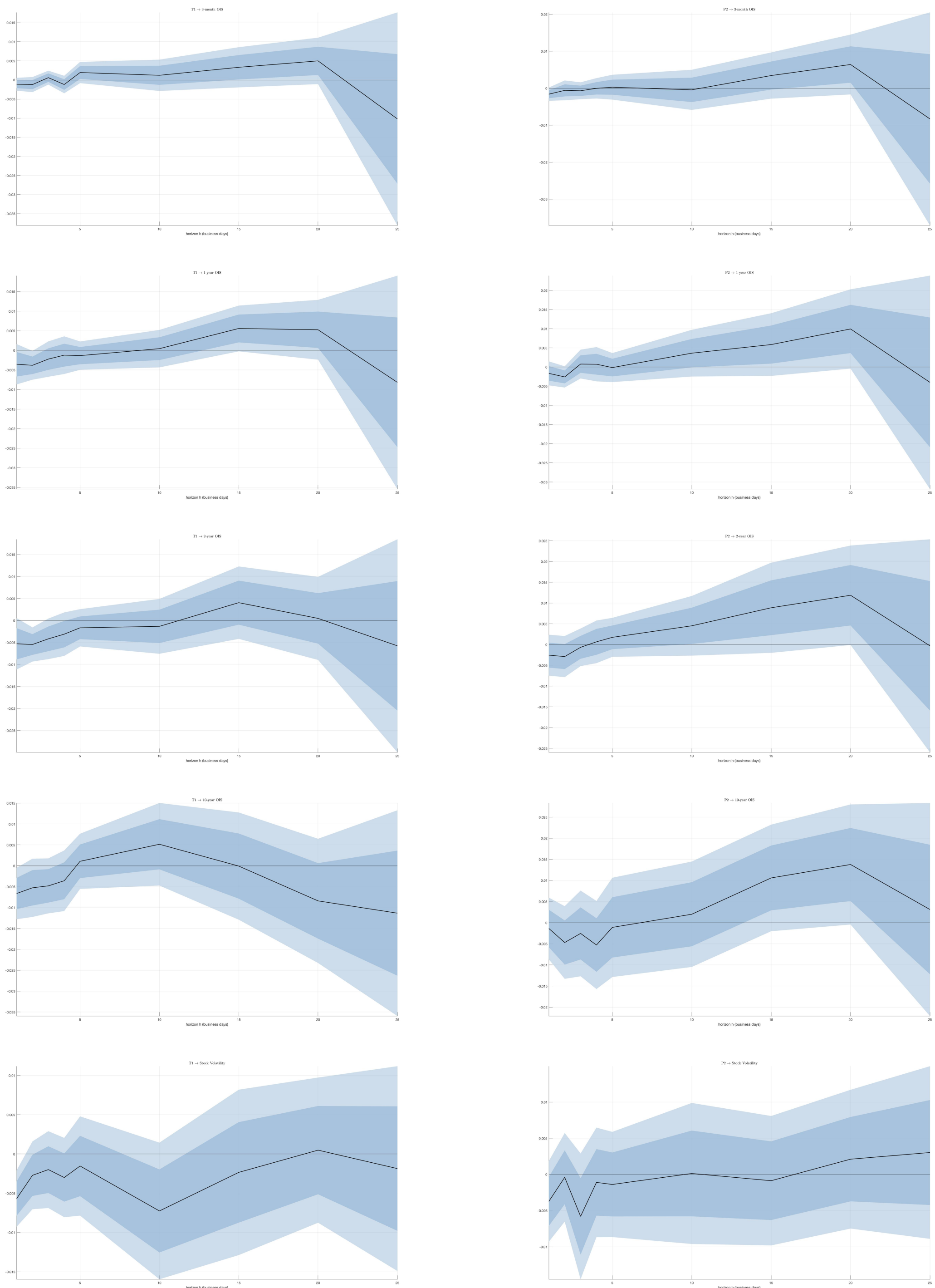

Figure 4: Daily local projection estimates following a 1-sample standard deviation shock of the target factor, $T1$, and the path factor, $P2$, respectively. One-standard deviation bands (68 per cent and 90 per cent probability) are reported. Note that the standard deviations are robust heteroskedastic and account for the uncertainty in the estimation of the shocks.

Figure 4 reports the results from the daily local projections where the variable x is the respective financial variable. The results highlight several key findings. Firstly, the responses across the OIS rates are consistent across the two shocks, $T1$ and $P2$. In particular, both carbon policy shocks have no persistent effect on the 3-month OIS rate, especially in the first 10 days. The greatest variation in the responses across horizons can be observed at longer maturities.

Moreover, the discrepancies between the two shocks are better reported for OIS rates at longer maturities. For instance, the path factor contributes to a persistent increase of the 1-year and 2-year OIS rates after 5 days, where the response becomes significant after 20 days. In contrast, the target factor only increases the 1-year and 2-year OIS rates after 10 days and remains insignificant.

The 10-year rate response displays the largest differences between the two shocks. While the 10-year rate initially responds negatively to both shocks, the target factor significantly declines the 10-year OIS rate before increasing and becomes negative again after 15 days. In contrast, the path factor contributes to significantly higher responses after 5 days, reaching its peak after 20 days, where this increase is significant.

Finally, both the target and the path factors contribute to lower stock volatility, albeit by different magnitudes. The target factor leads to a significant initial decline, but the negative response remains persistent throughout the horizons, except after 20 days. Similarly, the path factor leads to an initially negative response that remains persistent until after 15 days, with the response becoming positive yet insignificant.

5 Econometric Framework

As described in the previous section, we utilise high-frequency data to identify the carbon policy shock. Making use of daily data, we assume that up to a measurement error, the announcement of the outcome of a policy meeting is the only (exogenous) event that can impact carbon futures in a tight enough window around the EU ETS regulatory announcement. In turn, the movement of carbon futures in a daily window provides us with a relevant instrument for the carbon policy shock.

However, the carbon policy surprise series is only a partial measure of the shock of interest provided since there is a degree of measurement error (Stock & Watson 2018). As a result, I do not use the measure as a direct shock but rather as an instrument. The benefit of the model is that we are then able to use the high-frequency instrument as a basis for an external instrument, which is used to examine the dynamic effects of the carbon policy shock in a VAR framework. More specifically, I rely on Bayesian techniques to estimate an external instrument VAR model. Under the standard assumptions for the instruments in the model, I assume that the surprise series is correlated with the carbon policy shock but is uncorrelated with all other shocks.

5.1 Bayesian VAR model

Consider the following VAR model:

$$Y_t = X_t B + u_t \tag{10}$$

where Y_t is a N x 1 matrix of endogenous variables, $X_t = [Y_{t-1}, ..., Y_{t-P}, 1]$ represents the regressors in each equation and is $(NP+1)$ x 1. B is a N x $(NP+1)$ matrix of coefficients $B = [B_1, ..., B_P, c]$ and P are the lags. The reduced form residuals u_t have a covariance matrix that can be written as $Var(u_t) = \Sigma$, where $\Sigma = A_0 A_0'$ and where A_0 denotes the contemporaneous impact matrix. The reduced form residuals can be expressed as linear combinations of the structural shocks ε_t through the matrix A_0 as follows:

$$u_t = A_0 \varepsilon_t \tag{11}$$

By definition, ε_t denotes the uncorrelated structural shocks that are normally distributed and have a diagonal variance-covariance matrix, $Var(\varepsilon_t) = \Omega$. Assuming invertibility, the standard covariance restrictions apply such that $\Sigma = A_0 \Omega A_0'$. A column of the A_0 matrix corresponding to a specific shock can be estimated from the residuals of a VAR and a high-frequency instrument using the method of Mertens & Ravn (2013). Recall that in this paper, we are interested in estimating the impact of two high-frequency instruments, notably the action and the expected path instruments. Therefore, in the context of the model, the two high-frequency instruments identify two different contemporaneous responses at the monthly frequency. This can be denoted as the two columns of A_0, where $A_{0,k}$ and $k = 1, 2$.

The basis of the external instrument identification approach assumes that there exists an instrument m_t that satisfies the relevance and exogenous conditions as follows:

$$\mathbb{E}[m_t \varepsilon_{1,t}] = \alpha \neq 0 \tag{12}$$

$$\mathbb{E}[m_t \varepsilon_{2:n,t}] = 0 \tag{13}$$

We assume that $\varepsilon_{1,t}$ is the structural shock of interest, which in this case is the carbon policy shock. Alternatively, $\epsilon_{2:n,t}$ represents the $(n-1)$ x 1 vector of the remaining structural shocks in the model. Equation 12 is associated with the relevance condition of the instrument, implying that the instrument is correlated with the structural shock that is to be estimated and is testable. Equation 13 assumes that the instrument is exogenous and uncorrelated with the other shocks in the model. If both assumptions hold for the validity of the instrument m_t, then the first column of the A_0 matrix, a_1 is identified up to scale in the following way:

$$\tilde{a}_{1,1} \equiv \frac{a_{2:n,1}}{a_{1,1}} = \frac{\mathbb{E}[m_t u_{2:n,t}]}{\mathbb{E}[m_t u_{1,t}]} \tag{14}$$

To facilitate the interpretation of the shock, I normalise the carbon policy shock to increase HICP energy by 1 per cent. In other words, I assume $a_{1,1} = 1$ and assume that a unit positive value of $a_{1,1}$ has a unit positive effect on $Y_{1,t}$. The scale $a_{1,1}$ is set by a normalisation subject to $\Sigma = A_0 \Omega A_0'$. Having obtained the impact vector, we can compute the IRFs, FEVDs, and historical decompositions.

Recall that I derive two separate instruments (action and expected path) from the carbon policy shock using the orthogonal rotation described in the previous section. Nevertheless, for ease of interpretation, I simplify the notation and refer to $\varepsilon_{1,t}$ as the generic carbon policy shock that is of interest. Therefore, I estimate the impulse responses separately for the shock identified by the action instrument and the shock identified by the expected path instrument.

5.2 Estimation

I estimate the external instrument VAR model using Bayesian techniques similar in spirit to Miranda-Agrippino & Rey (2020). In particular, I impose a standard Normal-Wishart prior for the VAR coefficients as follows:

$$B|\Sigma \sim N(b, \Sigma \otimes \Omega) \tag{15}$$

$$\Sigma \sim IW(s, v) \tag{16}$$

where B is a vector including all the VAR parameters, s is diagonal where the elements are selected as a function of the residual variance of the regression of each variable onto its own first P lags. The degrees of freedom of the Inverse-Wishart are set such that the mean of the distribution exists and is equal to $v = n + 2$. The parameters in both equations are selected to match the moments for the distribution of the coefficients in 10 defined by the Minnesota priors:

$$\begin{aligned} \mathbb{E}\left[(B_i)_{jk}\right] &= \begin{cases} \delta_j & \text{for } i = 1, j = k \\ 0 & \text{otherwise} \end{cases} \\ \mathbb{V}\left[(B_i)_{jk}\right] &= \begin{cases} \frac{\lambda^2}{i^2} & \text{for } j = k \\ \frac{\lambda^2}{i^2}\frac{\sigma_k^2}{\sigma_j^2} & \text{otherwise} \end{cases} \end{aligned} \tag{17}$$

where $(B_i)_{jk}$ denotes the element in row (equation) j and column (variables) k of the coefficients matrix B at lag $i(i = 1, ..., P)$. When $\delta_j = 1$, the random walk prior is strictly imposed on all the variables. Otherwise, $\delta_j = 0$ is set for variables in which this prior is not suitable (Banbura et al. 2010). Secondly, the variance of all elements in B_i is assumed to be proportional to the (inverse of the) square of the lag (i^2) and to the relative variance of the variables. Finally, λ is the hyperparameter that dictates the overall tightness of the priors in the model. In particular, I treat λ as an additional parameter and estimate it following Giannone et al. (2015).

5.2.1 Prior specification

Following Banbura et al. (2010), I use a natural conjugate prior for the VAR parameters by incorporating dummy observations into the vector of variables as follows:

$$Y_{D,1} = \begin{pmatrix} diag(\gamma_1\sigma_1, \cdots, \gamma_N\sigma_N)/\tau \\ 0_{N\text{x}(P-1)\text{x}N} \\ \cdots\cdots\cdots\cdots\cdots\cdots\cdots \\ diag(\sigma_1, \cdots, \sigma_N) \\ \cdots\cdots\cdots\cdots\cdots\cdots\cdots \\ 0_{1\text{x}N} \end{pmatrix} \tag{18}$$

$$X_{D,1} = \begin{pmatrix} J_p \bigotimes diag(\sigma_1, \cdots, \sigma_N)/\tau & 0_{NP\text{x}1} \\ \cdots\cdots\cdots\cdots\cdots\cdots\cdots & \\ 0_{N\text{x}NP} & 0_{N\text{x}1} \\ \cdots\cdots\cdots\cdots\cdots\cdots\cdots & \\ 0_{1\text{x}NP} & c\text{x}I_1 \end{pmatrix} \tag{19}$$

where $J_p = diag(1, ..., P)$ denotes the number of lags in the model. In this specification, I set $P = 6$ since the frequency of our dataset is monthly. γ_1 to γ_N denotes the prior mean for the coefficients on the first lag, and τ measures the overall tightness of the prior on the VAR coefficients and is set to $\tau = 1$ whereas c controls the tightness of the prior on the constant. In this application, the prior means are chosen as the OLS estimates of the coefficients of an AR(1) regression estimated for each endogenous variable. As a result, σ_i are the scaling factors set using the standard deviation of the error terms from these preliminary AR(1) regressions.

In this application, I set $c = \frac{1}{10000}$ and impose a fairly flat prior on the constant. I also impose a prior on the sum of coefficients on the lagged dependent variables. This is implemented using dummy observations as follows:

$$Y_{D,2} = \frac{diag(\gamma_1\xi_1, ..., \gamma_N\xi_N)}{\lambda} \tag{20}$$

$$X_{D,2} = \begin{pmatrix} \frac{(1_{1\text{x}P}) \bigotimes diag(\gamma_1\xi_1, ..., \gamma_N\xi_N)}{\lambda} & 0_{N\text{x}1} \end{pmatrix} \tag{21}$$

where ξ_i denotes the sample mean for the $i'th$ endogenous variable calculated using AR(1) preliminary regressions. Finally, I set the tightness of the prior on the sum of coefficients to $\lambda = 10 * \tau$.

5.3 Empirical Specification

The baseline specification includes six variables. This includes the energy component of HICP, which is normalised to increase by 1 per cent following the carbon policy shock. Secondly, I include total GHG emissions to capture the effectiveness of the carbon policy shock in reducing emissions. Since emissions data is only available at an annual frequency, I construct a monthly measure of emissions using the Chow-Lin temporal disaggregation method. I use industrial production as the relevant monthly indicator, although this choice is robust to using HICP energy. The remaining four baseline variables capture the macroeconomic effects of the carbon policy shocks. This includes headline consumer prices, industrial production, the unemployment rate, and stock prices which are sourced from Refinitiv. I estimate the model using monthly data from January 1999 to December 2021. Recall that the carbon instrument is available from 2005 until 2023, given that the carbon futures data is available only from 2005.

Nevertheless, to improve the precision of the estimates of the model, I selected a longer sample and estimated the model from January 1999 rather than in 2005. To deal with the discrepancy in the years, I set the carbon surprise series to zero for the missing observations (Noh 2019). Finally, I estimate the VAR in levels. More specifically, all variables enter as log levels except for the unemployment rate and the two-year rate.

To better explore the dynamics of the impulse responses to the carbon policy shocks, I extend the baseline VAR to examine the wider propagation and transmission of the carbon policy shocks. Thus, I incorporate additional variables, including production, employment, and inflation expectations. I also include the two-year rate to capture the stance of monetary policy, real exchange rates, terms of trade, and the sub-indices for prices, including durables, non-durables, services, and core consumer prices. All the variables are available at monthly frequency and are obtained from Refinitiv.

6 Macroeconomic effects of carbon policy shocks

I present the results of the BVAR model using the baseline specifications. Figure 5 reports the impulse responses to the carbon policy shock identified by the action instrument, normalised to increase the HICP energy component by one per cent on impact. Also reported is the median over the saved draws, along with the 68 and 90 coverage set.

A tighter carbon policy shock triggers a sharp and significant increase in energy prices, providing evidence of the crucial channel that energy prices play in the transmission of carbon policy shocks. Moreover, our findings indicate that this carbon policy shock is inflationary, as evidenced by the positive response in headline consumer prices. While energy prices peak with a 1.97 per cent increase after four months, headline consumer prices show a smaller increase of 0.30 per cent after eight months. This smaller response of consumer prices compared to energy prices suggests that the impact of the carbon policy shock primarily operates through higher energy prices.

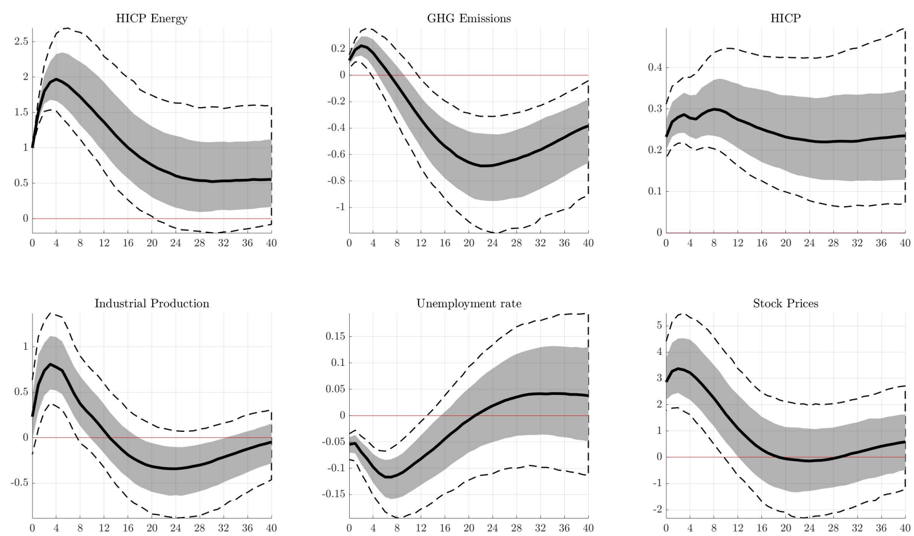

Figure 5: Impulse responses to a carbon policy shock identified by the action instrument

The carbon policy shock leads to a sustained decline in greenhouse gas (GHG) emissions. While this indicates that stricter carbon policies are effective in reducing overall emissions, we observe that the most significant negative impact occurs almost two years after the initial shock, resulting in a 0.69 percent reduction in emissions. This decline in emissions seems to be driven by a decrease in industrial production, suggesting that the carbon policy shock has contractionary effects on the economy, primarily through negative aggregate demand effects.

To illustrate this, the impulse responses of industrial production show similar patterns to the emissions response, mirroring the delayed negative effects of the shock. Notably, the decline in industrial production reaches its lowest point only after two years, showing a 0.34 percent decrease. This finding is consistent with Kanzig (2023), which indicates that while emissions decrease, this occurs at the cost of reduced industrial production. Furthermore, it is important to note that both industrial production and emissions only experience a decline after a substantial delay.

The impact of the carbon policy shock on headline consumer prices occurs more quickly than on other macroeconomic variables, which aligns with the findings presented by Kanzig (2023). For example, the delayed effect of the carbon policy shock is evident in the response of unemployment, which only begins to rise after several months. This observation is consistent with the gradual decline in industrial production. Similarly, stock prices exhibit a comparable response, reaching their lowest point only after two years, showing a reported decline of 0.15 per cent. In contrast to emissions and industrial production, the unemployment rate takes the longest to reflect the negative consequences of the shock. Overall, the results underscore the contractionary effects of the carbon policy shock on the economy, likely operating through negative aggregate demand effects that fully manifest after a few months.

Figure 6 illustrates the responses to the carbon policy shock identified by the expected path instrument. Similar to the action instrument, this carbon policy shock is normalized to increase energy prices by 1 per cent on impact. Our findings indicate that the responses exhibit similar dynamics to those observed with the action instrument, although the magnitudes of the responses vary across different variables.

For example, energy prices rise and reach a peak after four months, showing an increase of 1.20 per cent. This increase is relatively modest compared to the rise in energy prices resulting from the action instrument. This discrepancy may be attributed to the time it takes for producers to adjust their prices in anticipation of stricter carbon policy expectations. In contrast to the immediate price hikes triggered by a sudden tightening of carbon policy, the impact of expectations allows producers to modify their production scales. Although this adjustment leads to higher prices, the increases are not as pronounced as those associated with an immediate policy change.

Further support for this observation comes from the smaller positive response in headline consumer prices, which increase by a modest 0.11 per cent. In comparison, the increase from the carbon policy shock identified by the action instrument is 0.30 per cent.

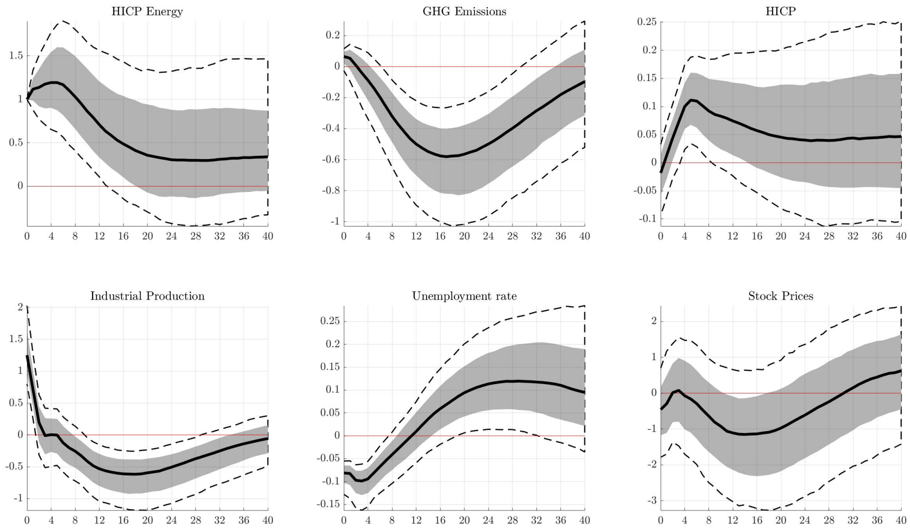

Figure 6: Impulse responses to a carbon policy shock identified by the expected path instrument

The expected path instrument has been found to contribute to higher prices, although these increases are smaller in magnitude compared to those generated by the action instrument. However, there are significant discrepancies in other macroeconomic and financial variables. Notably, the expected path instrument leads to more substantial negative economic effects, with these impacts manifesting more quickly than those associated with the action instrument.

For example, industrial production shows a persistent and significant decline a few months following the shock, reaching a minimum decrease of 0.62 per cent after one year. Similarly, emissions also decline, but they reach their lowest point at a faster rate compared to the decline caused by the action instrument. This rapid adjustment can be attributed to the immediate response in production prompted by the expected path instrument, which results in lower emissions and causes the effects of the shock to become apparent more quickly.

In line with the broader negative effects on aggregate demand, the unemployment rate rises following the shock, reaching a peak of 0.12 percent after 28 months, compared to a peak of 0.04 percent after 31 months. The expected path instrument also shows a stronger impact on stock prices, which decline immediately and remain negative for several months. Overall, the results indicate that while the action instrument influences prices significantly, the expected path instrument has a greater negative effect on demand, as evidenced by the more pronounced decreases in economic activity. This suggests that the expected path instrument functions as a form of forward guidance, prompting producers to adjust their production in a contractionary manner in anticipation of tighter future policies.

6.1 Historical contribution of carbon policy shocks

Provided that the carbon policy shocks identified both by the action instrument as well as the expected path instrument have significant effects on emissions and the macroeconomy, we may be interested in assessing how much of the historical variation of these respective variables can be attributed to the carbon policy shocks. To do this, I conduct a historical decomposition exercise to directly compare the importance of the action instrument relative to the expected path instrument in explaining the historical variation of the macroeconomic and financial series.

To compute the historical decompositions, we must ensure that the VAR model is stationary and is not applied to integrated or co-integrated variables in levels (Kilian & Lutkepohl 2017). As a result, I take the year-on-year growth rate of the variables in levels, excluding the interest rate, and estimate the baseline model using the same sample period from January 1999 to December 2021.

Figure 7 displays the cumulative historical contribution of the carbon policy shock identified by the action instrument on GHG emissions growth. Also reported are the actual values of the series in per cent deviations from the mean. The figure indicates that the shock significantly influences emissions growth and has led to notable fluctuations in the series over the sample period. However, the contributions from this shock are relatively larger in the latter half of the sample. Consistent with the findings of Känzig (2023), we observe that the substantial decrease in emissions following the global financial crisis was not primarily driven by the carbon policy shock, but rather by reduced activity due to lower demand. Specifically, the carbon policy shock accounts for only a modest 22 per cent decline in emissions growth during the financial crisis. This finding reinforces the effectiveness of the high-frequency identification approach as a suitable method for isolating the carbon policy shock.

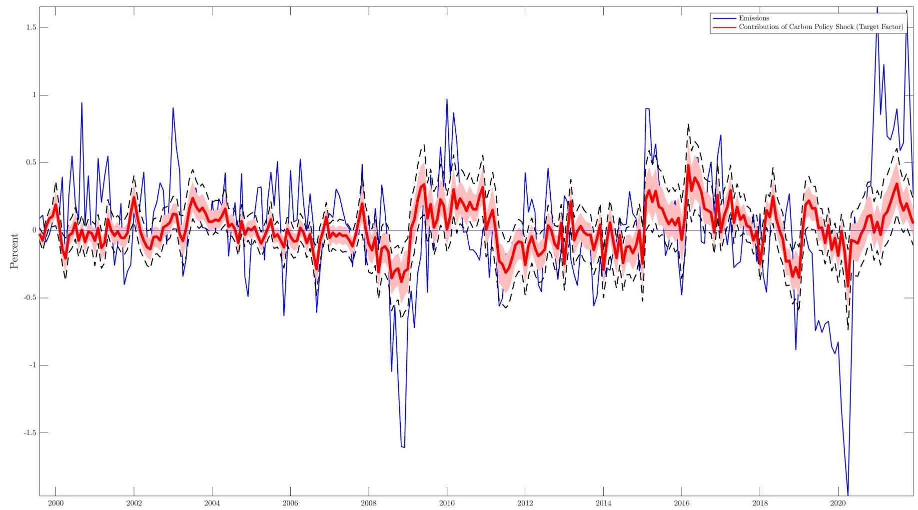

Figure 7: Historical decomposition of GHG emissions growth

Figure 8 illustrates the cumulative historical decomposition of energy price inflation alongside the actual values of energy price inflation, expressed as percentage deviations from the mean. On average, the carbon policy shock contributes to a greater variation in energy price inflation than it does in emissions growth. This observation remains consistent even during recessions. Specifically, approximately 30 per cent of the decline in energy price inflation during the global financial crisis can be attributed to the carbon policy shock.

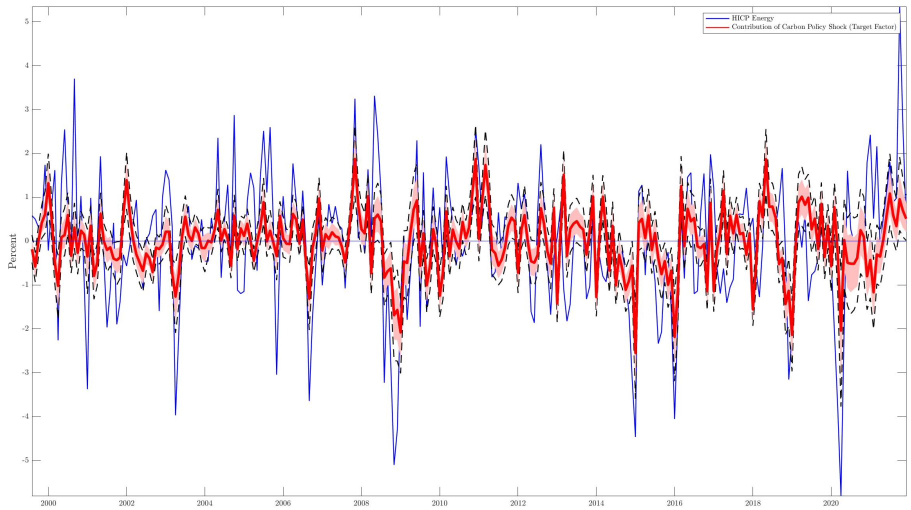

Figure 8: Historical decomposition of HICP energy inflation

To compare the findings across the two instruments, Figure 9 shows the cumulative historical contribution of carbon policy shock identified by the expected path instrument on GHG emissions growth, alongside the actual value of emissions growth in per cent deviations from the mean. In some cases, the contribution of the expected path instrument is smaller compared to that of the action instrument. For example, following the global financial crisis, the expected path instrument accounted for 14 per cent of the decline in emissions growth, while the action instrument explained approximately 22 per cent of the decline. However, there are significant discrepancies across the sample. During the COVID-19 recession, the expected path instrument had a much larger impact, contributing around 50 per cent to the decline in emissions growth, compared to just 21 per cent from the action instrument.

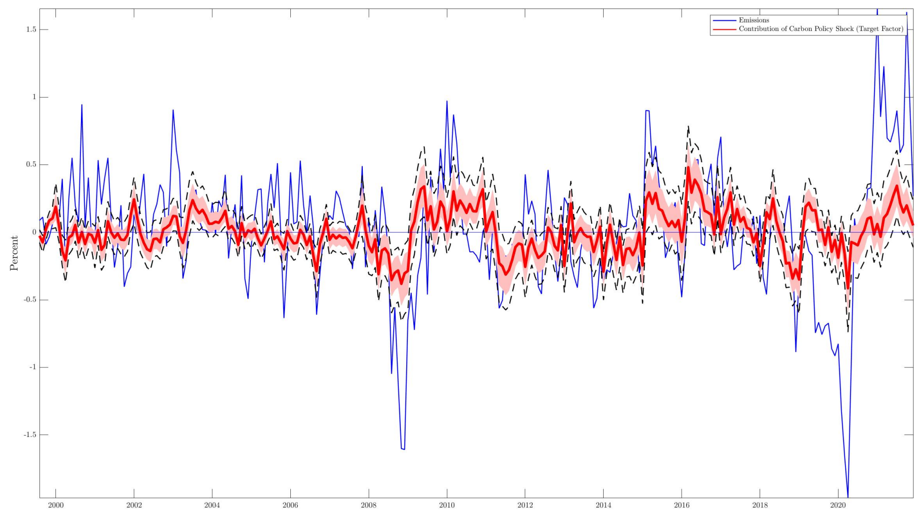

Figure 9: Historical decomposition of GHG emissions growth

Figure 10 illustrates the cumulative historical decomposition of energy price inflation, highlighting the differences in contributions from the two instruments. During the global financial crisis, the shock accounted for approximately 28 percent of the decline in energy price inflation, while the action instrument contributed around 30 percent. However, in more recent recessions, such as the COVID-19 recession, the expected path instrument explained a larger portion of the variation in energy price inflation, reaching nearly 60 percent, compared to the more modest 35 percent attributed to the action instrument. These findings align with the historical contributions observed for emissions growth.

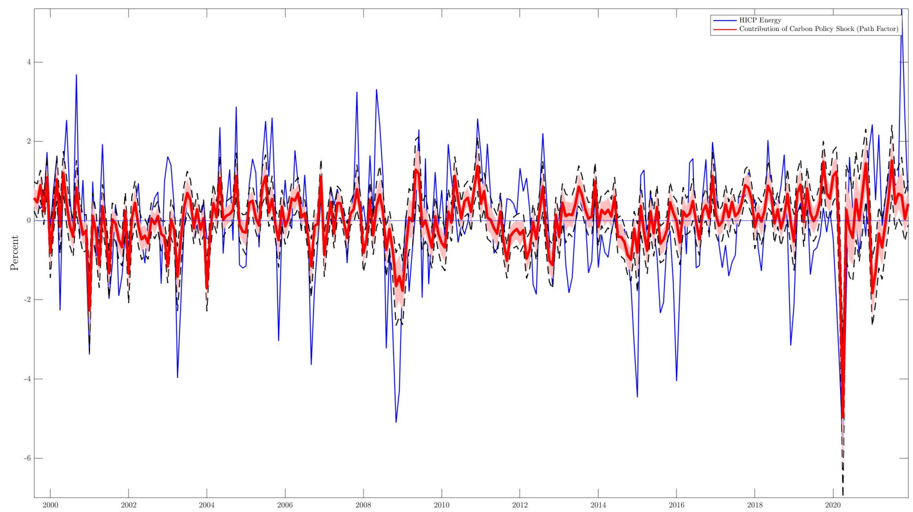

Figure 10: Historical decomposition of HICP energy inflation

6.2 Variance decompositions of carbon policy shocks

To further assess the economic significance of carbon policy shocks, I compute the share of forecast error variance of the baseline variables explained by both the carbon policy shocks identified by the action instrument and the expected path instrument.

Tables 3 and 4 present the variance decompositions of carbon policy shocks identified through the action and the expected path instruments, respectively. The results highlight significant differences in the contributions of the two instruments. Overall, the carbon policy shock identified by the action instrument results in a greater variation in the baseline variables compared to the shock identified by the expected path instrument. Specifically, the action instrument accounts for approximately 38 per cent of the short-run variation in energy prices, whereas the expected path

Table 3: Variance Decomposition (Action instrument)

h	HICP Energy	Emissions	HICP	IP	Unemp. rate	Stock prices
6	0.38	0.05	0.54	0.11	0.28	0.19
	[0.22, 0.54]	[0.01, 0.14]	[0.38, 0.67]	[0.03, 0.23]	[0.13, 0.44]	[0.07, 0.35]
12	0.38	0.06	0.50	0.11	0.20	0.16
	[0.20, 0.55]	[0.03, 0.15]	[0.32, 0.66]	[0.03, 0.23]	[0.07, 0.37]	[0.05, 0.33]
24	0.36	0.25	0.46	0.11	0.09	0.13
	[0.18, 0.54]	[0.08, 0.46]	[0.25, 0.66]	[0.04, 0.23]	[0.04, 0.22]	[0.05, 0.29]
36	0.34	0.35	0.46	0.12	0.08	0.13
	[0.16, 0.54]	[0.10, 0.55]	[0.22, 0.68]	[0.04, 0.26]	[0.03, 0.20]	[0.05, 0.28]

Table 4: Variance Decomposition (Expected path instrument)

h	HICP Energy	Emissions	HICP	IP	Unemp. rate	Stock prices
6	0.14	0.02	0.04	0.06	0.24	0.01
	[0.05, 0.27]	[0.01, 0.07]	[0.01, 0.13]	[0.02, 0.14]	[0.11, 0.39]	[0, 0.05]
12	0.12	0.11	0.04	0.07	0.09	0.01
	[0.04, 0.26]	[0.02, 0.24]	[0.01, 0.14]	[0.03, 0.13]	[0.04, 0.21]	[0, 0.06]
24	0.10	0.25	0.04	0.12	0.06	0.02
	[0.03, 0.24]	[0.08, 0.45]	[0.01, 0.14]	[0.04, 0.22]	[0.03, 0.13]	[0, 0.09]
36	0.10	0.25	0.04	0.12	0.06	0.03
	[0.03, 0.25]	[0.08, 0.46]	[0.01, 0.16]	[0.04, 0.25]	[0.02, 0.18]	[0, 0.11]

instrument contributes only 14 per cent.

Despite these differences, both shocks exhibit a decline in their contributions over time. Conversely, the carbon policy shock's contribution to emissions increases in the long run. The action instrument contributes to around 35 per cent of the variation in emissions, which is higher than the 25 per cent contributed by the expected path instrument.

The carbon policy shock identified by the action instrument accounts for approximately 54 per cent of the variation in headline consumer prices. In contrast, the expected path instrument explains a significantly smaller portion of this variation; however, its contribution is still noteworthy. This finding aligns with the observed variations in industrial production and the unemployment rate.

Interestingly, both instruments account for a larger share of the variation in industrial production over longer time horizons. On the other hand, when it comes to the unemployment rate, both shocks contribute to the most significant variation in the short term. Specifically, the action instrument explains 28 per cent of the variation, while the expected path instrument accounts for 24 per cent.

Regarding stock prices, the action instrument shows a declining contribution across different horizons, with its highest impact being 19 per cent in the short run. In contrast, the expected path instrument exhibits an increasing contribution to the variation of stock prices, reaching its peak at longer horizons.

7 Wider effects and transmission channels

To gain a better understanding of how carbon policy shocks transmit to the economy, I extend the baseline model to include a wide range of macroeconomic and financial variables. To compute the impulse responses, I extend the baseline VAR one variable at a time and subsequently estimate the model using seven variables each time.

7.1 Monetary policy, exchange rates and terms of trade

To investigate the monetary policy implications of carbon policy shocks, I estimate the impact of both the immediate action and the expected path instrument on the two-year interest rate. Examining this relationship is important because carbon policy shocks tend to increase prices while dampening economic activity. The results shown in the first panel of Figure 11 indicate that the action instrument leads to an increase in the two-year rate, peaking at a 0.15 per cent rise after 10 months. This finding suggests that monetary policy responds in a contractionary manner primarily to counteract the inflationary effects of the carbon policy shock. This aligns with Känzig (2023), which also finds that monetary policy reacts contractively, as evidenced by the increase in the two-year rate.

The carbon policy shock identified using the expected path instrument, as shown in the first panel of Figure 12, also confirms that monetary policy tends to contract in response to the higher prices indicated in the baseline model. However, there are notable discrepancies between the two instruments. For example, the two-year interest rate only increases by 0.12 per cent at its peak, which is smaller compared to the increase caused by the action instrument. This finding aligns with the baseline estimates, which indicate that the inflationary effects on both energy and headline consumer prices are relatively modest relative to the action instrument.

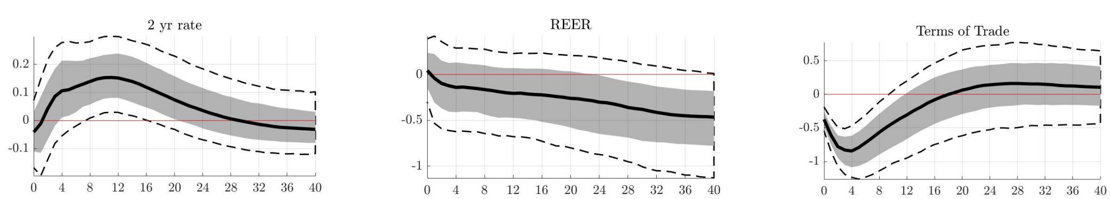

Figure 11: Impulse responses of monetary policy, exchange rates, and terms of trade to a carbon policy shock identified by the action instrument

I also examine the impact of carbon policy shocks on the real exchange rate. Following a carbon policy shock identified by the action instrument, the real exchange rate depreciates, as shown in the second panel of Figure 11. This depreciation may be a direct consequence of the inflationary effects that arise from the shock. Conversely, the expected path instrument initially results in a positive effect on the real exchange rate, but this turns negative after several years, as illustrated in the second panel of Figure 12.

Furthermore, I analyse the role of terms of trade in the aftermath of the carbon policy shock. The shock identified by the action instrument leads to a deterioration in terms of trade, which is evidenced by the contemporaneous negative and significant response depicted in the last panel of Figure 11. In contrast, the expected path instrument produces a positive response in terms of trade, as shown in the last panel of Figure 12. The variations in responses between the two instruments help to explain the differences in the baseline estimates reported.

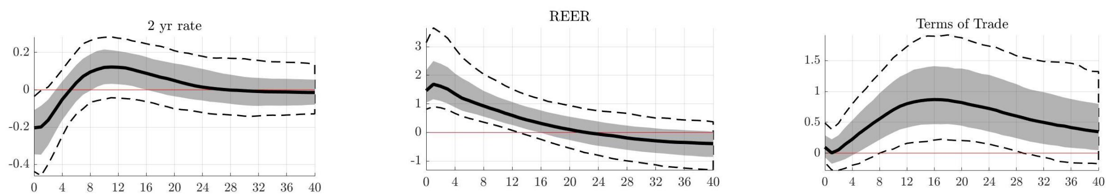

Figure 12: Impulse responses of monetary policy, exchange rates, and terms of trade to a carbon policy shock identified by the expected path instrument

7.2 Expectations

Given that carbon policy shocks propagate through future policy expectations, it is worth examining the role that both carbon policy shocks have on expectations. To this end, I collect data on production expectations, employment expectations, and inflation expectations from Refinitiv.

Figure 13 illustrates the responses to a carbon policy shock, as identified by the action instrument, concerning production expectations, employment expectations, and inflation expectations, which were added individually and estimated separately. The results affirm the impact of the carbon policy shock on industrial production, as indicated in the baseline model. Notably, production, employment, and inflation expectations show similar trends, with the most significant negative effects observed two years after the shock. These findings reinforce the baseline estimates, suggesting that the negative economic consequences of the carbon policy shock only materialise two years following the initial shock.

More interestingly, the responses of expectations to a carbon policy shock, as identified by the expected path instrument shown in Figure 14, reveal notable differences in both dynamics and magnitudes. As previously noted in the baseline model, the expected path instrument has a more

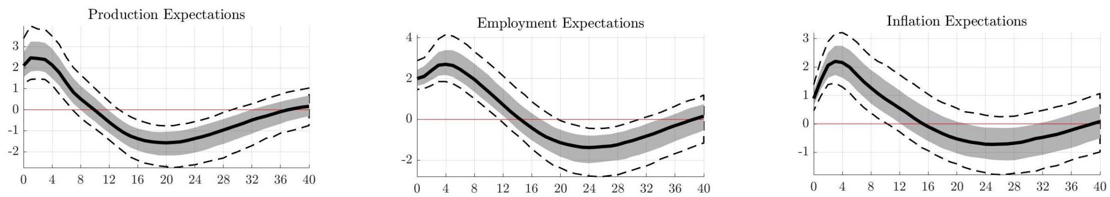

Figure 13: Impulse responses of expectations to a carbon policy shock identified by the action instrument

significant negative impact on macroeconomic aggregates, such as industrial production and unemployment. Therefore, we would anticipate that this would also be reflected in expectations.

Our findings confirm this, as the carbon policy shock leads to an immediate decline in expectations. Specifically, expectations for production and employment drop to their lowest point less than a year after the shock, indicating that the effects of the carbon policy shock are transmitted through the expectations channel. This is further supported by the faster decline in inflation expectations compared to the decrease caused by the carbon policy shock identified through the action instrument. Overall, these results underscore the stronger negative demand effects associated with the expected path instrument.

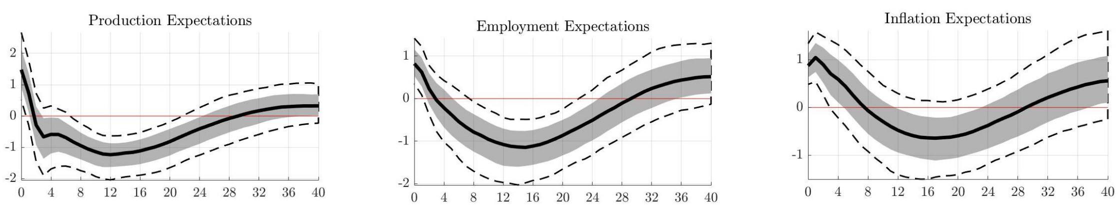

Figure 14: Impulse responses of expectations to a carbon policy shock identified by the expected path instrument

7.3 Consumer prices

Carbon policy shocks contribute to a significant increase in energy and headline consumer prices, as displayed in the baseline model. However, it is also worth considering the sub-indices for consumer prices to better understand the transmission of the carbon policy shock on prices. Therefore, I consider the responses of durables, non-durables, services, and core consumer prices.

Figure 15 shows the responses of various consumer price sub-indices following a carbon policy shock identified by the action instrument. Initially, there is a modest increase in core consumer prices; however, this increase is not significant in the short term and becomes more pronounced after several lags. In contrast, the prices of services rise significantly immediately after the shock, showing the largest increase compared to other sub-indices, although they decline consistently over the following months. Prices for durable goods also rise, but this increase is not statistically significant during the observed periods. Conversely, the prices of non-durable goods increase gradually over time and become statistically significant at longer lags.

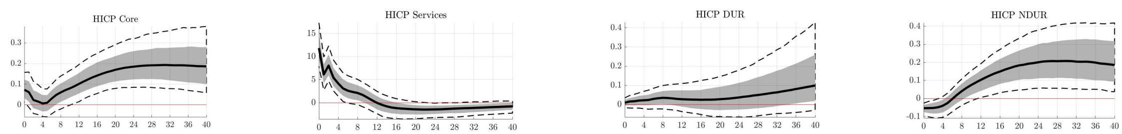

Figure 15: Impulse responses of consumer prices to a carbon policy shock identified by the action instrument

To compare the responses following a carbon policy shock identified by the expected path instrument, Figure 16 highlights key differences. Initially, the shock does not lead to an immediate rise in core prices; instead, it takes time for this shock to result in higher prices. The immediate negative impact corresponds with the responses observed in the services sector. In contrast to the shock identified by the action instrument, which causes a sharp increase in services, the expected path instrument indicates an initial decline in services, with an increase occurring only after several months.

In terms of durables and nondurables, the findings confirm this pattern. Specifically, durables initially decline in response to the carbon policy shock and do not recover until a few lags later. Their recovery remains subdued over time, which is consistent with the results from the action instrument. In contrast, nondurables show a persistent increase after a few periods, following a trajectory similar to that of the action instrument. Overall, these results suggest that the significant price increase associated with the action instrument is consistent across various categories of consumer prices.

Figure 16: Impulse responses of consumer prices to a carbon policy shock identified by the expected path instrument

8 Conclusion

Carbon policies are one of several tools that policymakers use to achieve lower emissions. In this paper, I focus specifically on the EU ETS carbon market to develop two new measures of carbon policy shocks. I utilise the high-frequency variation of a spectrum of carbon futures around 145 regulatory events related to the supply of emission allowances.

The main contribution of this paper is to expand the single-shock approach for identifying carbon policy shocks and to explore the influence of expectations regarding future carbon policies. Specifically, I decompose the high-frequency movements in carbon futures into two orthogonal instruments, which are extracted using the principal components analysis. To provide a structural interpretation to these factors, I apply a specific rotation to a subset of the principal components, resulting in two new instruments: the "action" instrument, which captures changes in the current policy rate and the “expected path” instrument, which captures changes in the expected path of future policy rates out to a horizon of three years, not inferred from the action itself. This paper aims to offer a new perspective on how expectations of future carbon policy are transmitted to the economy. To achieve this, I utilise the derived structural components to identify policy shocks within an external instrument (Bayesian) VAR model and analyse their dynamic macroeconomic implications.

The analysis, based on monthly data from January 1999 to December 2021, reveals significant effects of carbon policy shocks identified through the action instrument. While this shock effectively reduces emissions, it negatively impacts industrial production, unemployment, and stock prices. Notably, the most substantial negative effects occur two years after the initial carbon policy shock.

In contrast, the carbon policy shock identified by the expected path instrument produces even larger negative effects. These impacts manifest more quickly, with macroeconomic indicators, such as industrial production, reaching their lowest point after just one year. The magnitude of this decline is also more pronounced. These findings suggest that the expected path instrument results in more significant negative demand effects. This phenomenon may be explained by producers anticipating stricter future carbon policies, leading them to reduce production in advance. Consequently, this behaviour results in a more immediate decline in industrial production and an increase in the unemployment rate.

The results also reveal the inflationary effects of carbon policy shocks. Unlike macroeconomic aggregates, energy prices and overall consumer prices respond more quickly, demonstrating immediate increases in response to these shocks. Specifically, the carbon policy shock, identified through the action instrument, results in the most significant rise in energy prices and overall consumer prices. Hence, the carbon shock primarily affects prices through higher energy costs. In contrast, while the expected path instrument also leads to an increase in prices, this rise is comparatively smaller. This finding supports the notion that when producers foresee stricter future carbon policies, they have time to adjust their production processes, which helps prevent significant price increases.

By examining the effects of carbon policy shocks identified by both the action and expected path instruments separately, we have uncovered a new transmission channel that relies on information about future carbon policy expectations. This insight extends beyond what is understood from the action component alone. Our findings are supported by the variances and historical contributions, which highlight the differences between the two instruments. Specifically, the carbon policy shock identified by the action instrument accounts for a larger variation in baseline variables. However, the expected path instrument also significantly influences variations in emissions growth and energy price inflation, particularly during the COVID-19 recession. This indicates that the expected path has become a more relevant factor in recent times.

9 Appendix

9.1 Regulatory events

Table 5 outlines the key EU ETS regulatory events from 2005 to 2023, detailing the type of event and its corresponding date. In total, I have identified 145 regulatory events within the sample period.

Table 5: EU ETS Regulatory update events

	Date	Event	Type
1	25/05/2005	Italian phase I NAP approved	Free alloc.
2	20/06/2005	Greek phase I NAP approved	Free alloc.
3	23/11/2005	Proposed amendment to NAP, UK vs. Comission	Free alloc.
4	22/12/2005	Allocation plans for 2008–2012 period	Cap
5	22/02/2006	Final UK Phase I NAP approved	Free alloc.
6	23/10/2006	Stavros Dimas signal to tighten cap of phase II	Cap
7	13/11/2006	Decision avoiding double counting of emission reductions	Intl. credits
8	29/11/2006	Commission decision on the NAP of several member states	Free alloc.
9	14/12/2006	Decision determining emission levels	Cap
10	16/01/2007	Phase II NAPs of Belgium and the Netherlands approved	Free alloc.
11	05/02/2007	Slovenia phase II NAP approved	Free alloc.
12	26/02/2007	Spain phase II NAP approved	Free alloc.
13	26/03/2007	Phase II NAPs of Poland, France and Czech Republic approved	Free alloc.
14	02/04/2007	Austrian phase II NAP approved	Free alloc.
15	16/04/2007	Hungarian phase II NAP approved	Free alloc.
16	30/04/2007	Court order on German NAP, EnBW AG vs Commission	Free alloc.
17	04/05/2007	Estonian phase II NAP approved	Free alloc.
18	15/05/2007	Italian phase II NAP approved	Free alloc.
19	07/11/2007	Court judgement on German NAP, Germany vs Commission	Free alloc.
20	08/04/2008	Order on German NAP, Saint-Gobain Glass GmbH vs Commission	Free alloc.
21	23/04/2009	Amending Directive to improve and extend the EU ETS	Cap
22	23/09/2009	Court judgement on NAP, Poland vs Commission	Free alloc.
23	24/12/2009	Decision determining sectors and subsectors	Free alloc.
24	19/04/2010	Commission accepts Polish NAP for 2008-2012	Free alloc.
25	09/07/2010	Commission determining cap on emission allowances for 2013	Cap
26	14/07/2010	Commission backed for proposed rules for auctioning	Auction
27	22/10/2010	Cap on emission allowances for 2013 adopted	Cap
28	12/11/2010	Commission formally adopted the regulation on auctioning	Auction
29	25/11/2010	Proposal to restrict use of credits in industrial gas projects	Intl. credits
30	15/12/2010	Proposal on how to allocate emissions rights	Free alloc.

	Date	Event	Type
31	21/01/2011	Member states support ban on the use of certain industrial gas credits	Intl. credits
32	15/03/2011	Commission proposed that 120 million allowances auctioned in 2012	Auction
33	22/03/2011	Court judgement on NAP, Latvia vs Commission	Free alloc.
34	29/03/2011	Decision on transitional free allocation of allowances to the power sector	Free alloc.
35	27/04/2011	Decision on transitional Union-wide rules for free allocation of allowances	Free alloc.
36	29/04/2011	Commission rejects Estonia's revised NAP for 2008-2012	Free alloc.
37	07/06/2011	Commission adopts ban on the use of industrial gas credits	Intl. credits
38	13/07/2011	Member states agree to auction 120 million phase III allowances in 2012	Auction
39	26/09/2011	Commission sets rules for allocation of free emissions allowances to airlines	Free alloc.
40	14/11/2011	Clarification on the use of international credits in the third trading phase	Intl. credits
41	23/11/2011	Regulation on volume of allowances to be auctioned prior to 2013	Auction
42	25/11/2011	Update on preparatory steps for auctioning of phase 3 allowances	Auction
43	05/12/2011	Commission decision on revised Estonian NAP for 2008-2012	Free alloc.
44	29/03/2012	Court judgments on NAPs for Estonia and Poland	Free alloc.
45	02/05/2012	Published guidelines for review of GHG inventories to set limits for 2013-20	Cap
46	23/05/2012	Temporary free allowances in Cyprus, Estonia, Lithuania cleared	Free alloc.
47	05/06/2012	Guidelines on State aid measures for post-2012 trading scheme published	Free alloc.
48	06/07/2012	Temporary free allowances in Bulgaria, Czech, Romania cleared	Free alloc.
49	13/07/2012	Commission rules on temporary free allowances for power plants in Poland	Free alloc.
50	25/07/2012	Proposal to back-load allowances from 2013-2015 to end of phase III	Auction
51	12/11/2012	Amendment to back-load 900 million allowances for 2019-2020	Auction
52	14/11/2012	Options to reform ETS to address supply-demand imbalance	Cap
53	16/11/2012	Auctions for 2012 aviation allowances put on hold	Auction
54	30/11/2012	Rules on temporary free allowances for power plants in Hungary	Free alloc.
55	25/01/2013	Update on free allocation of allowances in 2013	Free alloc.
56	28/02/2013	Free allocation of 2013 aviation allowances postponed	Free alloc.
57	25/03/2013	Auctions of aviation allowances not to resume before June	Auction
58	16/04/2013	Parliament voted against the Commission's back-loading proposal	Auction
59	05/06/2013	Proposal for international credit entitlements for 2013 to 2020 submitted	Intl. credits
60	03/07/2013	The EU Parliament voted for the carbon market back-loading proposal	Auction

	Date	Event	Type
61	10/07/2013	States approve addition of sectors to carbon leakage list for 2014	Free alloc.
62	30/07/2013	Update on industrial free allocation for phase III	Free alloc.
63	05/09/2013	Commission finalized decision on industrial free allocation for phase three	Free alloc.
64	26/09/2013	Update on number of aviation allowances to be auctioned in 2012	Auction
65	08/11/2013	Member states endorsed negotiations on the back-loading proposal	Auction
66	21/11/2013	Commission submitted non-paper on back-loading to EU C.C Committee	Auction
67	10/12/2013	European Parliament voted for the back-loading proposal	Auction
68	11/12/2013	C.C Committee makes progress on implementing back-loading proposal	Auction
69	18/12/2013	First set of member states to allocate allowances for year 2013	Free alloc.
70	08/01/2014	Climate Change Committee agrees back-loading	Auction
71	22/01/2014	Commission proposed to establish a market stability reserve for phase V	Cap
72	26/02/2014	Commission gives green light for free allocation by all member states	Free alloc.
73	27/02/2014	Back-loading: 2014 auction volume reduced by 400 million allowances	Auction
74	13/03/2014	Commission approves first batch of international credit entitlement tables	Intl. credits
75	28/03/2014	Commission approves second batch of intl. credit entitlement tables	Intl. credits
76	04/04/2014	Update on approval of international credit entitlement tables	Intl. credits
77	11/04/2014	Commission approves four more international credit entitlement tables	Intl. credits
78	23/04/2014	Commission approves final international credit entitlement tables	Intl. credits
79	02/05/2014	Commission published the number of international credits exchanged	Intl. credits
80	05/05/2014	Commission submits proposed carbon leakage list for 2015-2019	Free alloc.
81	04/06/2014	Auctioning of aviation allowances to restart in September	Auction
82	04/07/2014	First update on allocation of allowances from New Entrants' Reserve	Free alloc.
83	09/07/2014	C.C Committee agrees proposed carbon leakage list for 2015-2019	Free alloc.
84	27/10/2014	Commission adopts the carbon leakage list for the period 2015-2019	Free alloc.
85	04/11/2014	Updated information on exchange and international credit use	Intl. credits
86	04/05/2015	Updated information on exchange and international credit use	Intl. credits
87	15/07/2015	Proposal to revise the EU emissions trading system for the period after 2020	Cap
88	23/07/2015	Status update for New Entrants' Reserve and allocation reductions	Free alloc.
89	04/11/2015	Updated information on exchange and international credit use	Intl. credits
90	15/01/2016	Commission publishes status update for New Entrants' Reserve	Free alloc.

	Date	Event	Type
91	28/04/2016	Court judgment on free allocation in the EU ETS for the period 2013-2020	Free alloc.
92	02/05/2016	Updated information on exchange and international credit use	Intl. credits
93	23/06/2016	Commission to modify cross-sectoral correction factor for 2018-2020	Free alloc.
94	15/07/2016	Updates on allocation of allowances from New Entrants' Reserve 2013-2020	Free alloc.
95	08/09/2016	Court judgment on free allocation in the EU ETS for the period 2013-2020	Free alloc.
96	04/11/2016	Updated information on exchange and international credit use	Intl. credits
97	16/01/2017	Commission publishes status update for New Entrants' Reserve	Free alloc.
98	24/01/2017	Decision to implement Court ruling on the cross-sectoral correction factor	Free alloc.
99	15/02/2017	EU Parliament in support of the ETS Directive revision for after 2021	Cap
100	27/04/2017	Climate Change Committee approves technical changes to auction rules	Auction
101	02/05/2017	Updated information on exchange and international credit use	Intl. credits
102	12/05/2017	First surplus indicator for ETS Market Stability Reserve published	Auction
103	17/07/2017	Commission publishes status update for New Entrants' Reserve	Free alloc.
104	26/07/2017	Confirmation of benchmark for free allocation of allowances for 2013-2020	Free alloc.
105	06/11/2017	Updated information on exchange and international credit use	Intl. credits
106	15/01/2018	Commission publishes status update for New Entrants' Reserve	Free alloc.
107	04/05/2018	Updated information on exchange and international credit use	Intl. credits
108	08/05/2018	Commission Notice on carbon leakage list for phase IV (2021-2030)	Free alloc.
109	15/05/2018	ETS Market Stability Reserve reduce auctions by almost 265m allowances	Auction
110	16/07/2018	Commission publishes status update for New Entrants' Reserve	Free alloc.
111	30/10/2018	Commission adopts amendment to ETS auctioning regulation	Auction
112	06/11/2018	Updated information on exchange and international credit use	Intl. credits
113	05/12/2018	Poland's 2019 auctions include allowances not used for power sector	Auction
114	04/01/2019	Amendment to the ETS auctioning regulation	Auction
115	15/01/2019	Commission publishes status update for New Entrants' Reserve	Free alloc.
116	15/02/2019	Adoption of the Delegated Decision on the carbon leakage list for 2021-2030	Free alloc.
117	23/04/2019	Iceland, Liechtenstein, and Norway to start auctions on auction platform	Auction
118	15/05/2019	ETS Market Stability Reserve reduce auctions by almost 400m allowances	Auction
119	16/05/2019	Revised 2019 auction calendars including EEA EFTA volumes published	Auction
120	12/06/2019	Poland's 2020 auction volume include allowances not used for power sector	Auction

	Date	Event	Type
121	19/06/2019	Updated information on exchange and international credit use	Intl. credits
122	11/07/2019	2020 and 2019 auction calendars of the common auction platform published	Auction
123	15/07/2019	Commission publishes status update for New Entrants' Reserve	Free alloc.
124	28/08/2019	Commission amends ETS auctioning regulation for phase 4	Auction
125	31/10/2019	Regulation on adjustments to free allocation due to activity level changes	Free alloc.
126	08/11/2019	Auctioning regulation amendment for phase 4 to enter into force	Auction
127	15/01/2020	Commission publishes status update for New Entrants' Reserve	Free alloc.
128	08/05/2020	ETS Market Stability Reserve reduce auctions by 330m allowances	Auction
129	08/05/2020	Updated information on exchange and international credit use	Intl. credits
130	18/05/2020	Commission launches call for tenders for the third common auction platform	Auction
131	17/11/2020	Start of phase 4: Adoption of the cap and start of the auctions	Auction
132	11/12/2020	Allowances issued to aircraft operators and the Market Stability Reserve	Auction
133	15/03/2021	Adoption of the regulation determining benchmark values for free allocation	Free alloc.
134	12/05/2021	ETS Market Stability Reserve reduce auctions by 378 million allowances	Auction
135	25/05/2021	Updated information on exchange and international credit use	Intl. credits
136	31/05/2021	Adoption of uniform cross-sectoral correction factor applied to free allocation	Free alloc.
137	29/06/2021	Commission publishes the national allocation tables	Auction
138	12/05/2022	ETS Market Stability Reserve reduce auctions by 347m allowances	Auction
139	15/05/2023	ETS Market Stability Reserve reduce auctions by 272m allowances	Auction
140	28/07/2023	Decision on the union-wide quantity of allowances for 2024	Free alloc.
141	30/08/2023	Upcoming EU Hydrogen Bank pilot auction	Auction
142	17/10/2023	Commission adopts new ETS Auctioning Regulation for Fit for 55	Auction
143	31/10/2023	Commission decides on 2024 allowances for aircraft operators	Free alloc.
144	16/11/2023	Notice of provisional auction volume of general and aviation allowances	Auction
145	23/11/2023	Commission launches first European Hydrogen Bank auction	Auction

References

Andersson, J. J. (2019), 'Carbon Taxes and CO2 Emissions: Sweden as a Case Study', *American Economic Journal: Economic Policy* **11**(4), 1–30.

Banbura, M., Giannone, D. & Reichlin, L. (2010), 'Large Bayesian vector auto regressions', *Journal of Applied Econometrics* **25**(1), 71–92.

Beechey, M. & Österholm, P. (2007), The rise and fall of u.s. inflation persistence, Finance and Economics Discussion Series 2007-26, Board of Governors of the Federal Reserve System (U.S.).

Benmir, G. & Roman, J. (2022), The distributional costs of net-zero: A hank perspective, Technical report, Working paper.

Bernard, J.-T., Islam, M. & Kichian, M. (2018), Effects of B.C.'s Carbon Tax on GDP, Working Papers 1812E, University of Ottawa, Department of Economics.

Bernard, J.-T. & Kichian, M. (2021), 'The Impact of a Revenue-Neutral Carbon Tax on GDP Dynamics: The Case of British Columbia', *The Energy Journal* **0**(Number 3), 205–224.

Comission, E. (2020a), Eu emissions trading system (eu ets), Technical report.

Demirer, R. & Kutan, A. (2010), 'The behavior of crude oil spot and futures prices around opec and spr announcements: An event study perspective', *Energy Economics* **32**(6), 1467–1476.

Ellingsen, T. & Söderström, U. (2004), Why Are Long Rates Sensitive to Monetary Policy?, Working Paper Series 160, Sveriges Riksbank (Central Bank of Sweden).

Fan, Y., Jia, J.-J., Wang, X. & Xu, J.-H. (2017), 'What policy adjustments in the eu ets truly affected the carbon prices?', *Energy Policy* **103**(C), 145–164.

Gertler, M. & Karadi, P. (2015), 'Monetary policy surprises, credit costs, and economic activity', *American Economic Journal: Macroeconomics* **7**(1), 44–76.

Giannone, D., Lenza, M. & Primiceri, G. E. (2015), 'Prior Selection for Vector Autoregressions', *The Review of Economics and Statistics* **97**(2), 436–451.

Gürkaynak, R. S., Sack, B. & Swanson, E. (2005), 'Do Actions Speak Louder Than Words? The Response of Asset Prices to Monetary Policy Actions and Statements', *International Journal of Central Banking* **1**(1).

Hengge, M., Panizza, U. & Varghese, R. (2023), 'Carbon policy surprises and stock returns: Signals from financial markets', *SSRN Electronic Journal* .

Jarociński, M. (2024), 'Estimating the fed's unconventional policy shocks', *Journal of Monetary Economics* **144**, 103548.

Kaminska, I., Mumtaz, H. & Šustek, R. (2021), 'Monetary policy surprises and their transmission through term premia and expected interest rates', *Journal of Monetary Economics* **124**, 48–65.

Kilian, L. & Lutkepohl, H. (2017), *Structural Vector Autoregressive Analysis*, Cambridge University Press.

Konradt, M. & di Mauro, B. W. (2021), Carbon Taxation and Greenflation- Evidence from Europe and Canada, IHEID Working Papers 17-2021, Economics Section, The Graduate Institute of International Studies.

Konradt, M., McGregor, T. & Toscani, M. F. G. (2024), Carbon Prices and Inflation in the Euro Area, IMF Working Papers 2024/031, International Monetary Fund.

Kuttner, K. N. (2001), 'Monetary policy surprises and interest rates: Evidence from the Fed funds futures market', *Journal of Monetary Economics* **47**(3), 523–544.

Känzig, D. R. (2021), 'The macroeconomic effects of oil supply news: Evidence from opec announcements', *American Economic Review* **111**(4), 1092–1125.

Känzig, D. R. (2023), The Unequal Economic Consequences of Carbon Pricing, NBER Working Papers 31221, National Bureau of Economic Research, Inc.

Känzig, D. R. & Konradt, M. (2023), Climate Policy and the Economy: Evidence from Europe's Carbon Pricing Initiatives, NBER Working Papers 31260, National Bureau of Economic Research, Inc.

Martin, R., de Preux, L. B. & Wagner, U. J. (2014), 'The impact of a carbon tax on manufacturing: Evidence from microdata', *Journal of Public Economics* **117**(C), 1–14.

McKibben, W. B., Umstead, L. K. & Borders, L. D. (2017), 'Identifying dynamics of counseling leadership: A content analysis study', *Journal of Counseling & Development* **95**(2), 192–202.

Mertens, K. & Ravn, M. O. (2013), 'The dynamic effects of personal and corporate income tax changes in the united states', *American Economic Review* **103**(4), 1212–47.

Metcalf, G. E. (2019), 'On the Economics of a Carbon Tax for the United States', *Brookings Papers on Economic Activity* **50**(1 (Spring), 405–484.

Metcalf, G. E. & Stock, J. H. (2020), 'Measuring the macroeconomic impact of carbon taxes', *AEA Papers and Proceedings* **110**, 101–06.

Miranda-Agrippino, S. & Rey, H. (2020), 'U.S. Monetary Policy and the Global Financial Cycle', *The Review of Economic Studies* **87**(6), 2754–2776.

Moessner, R. (2022), Effects of Carbon Pricing on Inflation, CESifo Working Paper Series 9563, CESifo.

Mumtaz, H., Saleheen, J. & Spitznagel, R. (2023), Keep it Simple: Central Bank Communication and Asset Prices, Working Papers 960, Queen Mary University of London, School of Economics and Finance.

Murray, B. & Rivers, N. (2015), 'British columbia's revenue-neutral carbon tax: A review of the latest "grand experiment" in environmental policy', *Energy Policy* **86**(C), 674–683.

Nakamura, E. & Steinsson, J. (2018), 'High-Frequency Identification of Monetary Non-Neutrality: The Information Effect*', *The Quarterly Journal of Economics* **133**(3), 1283–1330.

Nishigaki, H. (2023), 'The impact of rising eu allowance prices on core inflation in the eurozone', *Economic Affairs* **43**(2), 245–264.

Noh (2019), 'Impulse-response analysis with proxy variables'.

Rafaty, R., Dolphin, G. & Pretis, F. (2020), Carbon pricing and the elasticity of CO2 emissions, Working papers, Energy Policy Research Group, Cambridge Judge Business School, University of Cambridge.

Rigobon, R. & Sack, B. (2004), 'The impact of monetary policy on asset prices', *Journal of Monetary Economics* **51**(8), 1553–1575.

Stefan, M. & Wellenreuther, C. (2020), 'London vs. Leipzig: Price discovery of carbon futures during Phase III of the ETS', *Economics Letters* **188**(C).

Stock, J. H. & Watson, M. W. (2018), 'Identification and Estimation of Dynamic Causal Effects in Macroeconomics Using External Instruments', *Economic Journal* **128**(610), 917–948.