University of Pretoria
Department of Economics Working Paper Series

Time-Variation in the Persistence of Carbon Price Uncertainty: The Role of Carbon Policy Uncertainty

Oguzhan Cepni
Ostim Technical University, University of Edinburgh Business School, and Copenhagen Business School
Luis A. Gil-Alana
University of Navarra and Universidad Francisco de Vitoria
Rangan Gupta
University of Pretoria
Onur Polat
Bilecik Şeyh Edebali University
Working Paper: 2024-46
October 2024

Department of Economics
University of Pretoria
0002, Pretoria
South Africa
Tel: +27 12 420 2413

Time-Variation in the Persistence of Carbon Price Uncertainty: The Role of Carbon Policy Uncertainty

Oguzhan Cepni[*], Luis A. Gil-Alana[**], Rangan Gupta[***] and Onur Polat[****]

Abstract

We estimate models of fractional integration to determine the degree of persistence for two recently developed metrics of carbon price uncertainty: the Carbon VIX and Carbon Implied Volatility (CIV) covering the period of the 1st week of September 2013 to the 4th week of December 2022. First, we find the two metrics to be highly persistent but depicting mean-reversion with long-memory. Second, time-varying (recursive) estimation revealed that the underlying persistence is on a downward trend. Third, we show that the recent declines in persistence of carbon price uncertainties is a result of declining carbon policy uncertainty, the metric of which we develop using aggregate information on squared surprises of carbon futures price of various maturities. Given that carbon price uncertainty has been shown to negatively affect decarbonization investments, our findings have important implications for the European Union Emissions Trading System (EU-ETS).

Keywords: Carbon Price Uncertainty; Fractional Integration; Persistence; Regulatory Events; Carbon Policy Uncertainty.

JEL Codes: C22; C32; D80, Q52.

1. Introduction

Understanding how uncertainty in carbon prices affects behavior of firms is essential, as it influences their ability and willingness to commit to long-term investments aimed at reducing emissions, and hence, shaping the global transition toward decarbonization. Given this, in their recent work, Fuchs et al. (2024) studied this relationship by analyzing how carbon price uncertainty impact decisions of firms to decarbonize their operations. To achieve their objective, the authors first developed two high-frequency (weekly) measures of carbon price uncertainty namely, the Carbon VIX (CVIX) and Carbon Implied Volatility (CIV). The construction of the CVIX, which follows the methodology of the Chicago Board Options Exchange (CBOE)'s Volatility index (VIX) of S&P 500 stock price uncertainty, is based on building a portfolio of options whose final payoff approximates the realized variance of the European Union emission allowance (EUA) futures until option expiry. As far as the CIV is concerned, it measures expected EUA price volatility via the "implied volatility" of at-the-money options. Second, Fuchs et al.

[*] Ostim Technical University, Ankara, Turkiye; University of Edinburgh Business School, Centre for Business, Climate Change, and Sustainability; Department of Economics, Copenhagen Business School, Denmark. Email address: oce.eco@cbs.dk.
[**] Faculty of Economics and ICS, University of Navarra, E-31080 Pamplona, Spain; Universidad Francisco de Vitoria, Facultad de Ciencias Juridicas y Empresariales, Madrid, Spain. Email address: alana@unav.es.
[***] Department of Economics, University of Pretoria, Private Bag X20, Hatfield 0028, South Africa. Email address: rangan.gupta@up.ac.za.
[****] Department of Public Finance, Bilecik Şeyh Edebali University, Bilecik, Turkiye. Email address: onur.polat@bilecik.edu.tr.

(2024) analyzed the effect of the Carbon VIX and CIV on the stock returns of firms that help other businesses to decarbonize, wherein these "carbon solution providers" are identified by extracting common types of decarbonization investments from a large survey of firms, and then by selecting companies that offer the associated goods and services. The study found that the stock returns, proxying for expected decarbonization investments, of these carbon solution providers are negatively impacted by the two metrics of carbon price uncertainty. The main implication of these findings is that it provides support to the predictions from real options theory associated with general uncertainty (Bloom, 2009), whereby firms are expected to delay investments in decarbonization when faced with uncertainty about the future costs of emissions.

Against this backdrop, in the context of the global policy objective of reducing aggregate carbon emissions to mitigate climate change, a pertinent issue is determining the underlying persistence of carbon price uncertainty. This is because the degree of persistence in Carbon VIX and CIV would govern the time it would take a shock in carbon price uncertainty to die-off. Put differently, persistence refers to the extent to which shocks in carbon price volatility, captured by CVIX and CIV, have lasting effects. A key policy concern is that if the degree of persistence is high, the adverse impact of carbon price uncertainty on decarbonization investments will be prolonged, thereby slowing down the process of mitigation associated with climate risks. Given this, in this paper, we utilize models of fractional integration to determine the estimates of persistence for Carbon VIX and CIV over the period of the 1st week of September 2013 to the 4th week of December 2022. In addition to the full-sample analysis, we estimate the econometric models in a recursive manner over the period of the 3rd week (19th) of December 2015, which corresponds to a week after the Paris Agreement[1] was drafted, to examine the evolving pattern in the degree of persistence of carbon price uncertainty. Similar to the full-sample analysis, the recursive estimation, indicative of the trend in the process of persistence, should be of immense value to policymakers in determining the level of intervention that might be required to reduce the uncertainty surrounding carbon pricing.

To the best of our knowledge, this is the first paper to analyze the degree of full-sample and time-varying persistence of carbon price uncertainty of the European Union Emissions Trading System (EU-ETS), as well as trying to explain the trend in persistence by developing a measure of uncertainty involving policies related to carbon pricing. By examining how the persistence of uncertainty evolves, we add to the studies that have previously depicted high-levels of (time-varying) persistence, i.e., long-memory, primarily based on models of fractional integration, of general international and regional macroeconomic and financial uncertainties (see, for example, Plakandaras et al. (2019), Gil-Alana and Payne (2020), Abakah, et al. (2021), Solarin and Gil-Alana (2021), and Sheng et al. (2022)). In addition, by creating a metric of uncertainty involving policies of carbon pricing, we also contribute to the large literature on developing varied measures of policy related uncertainties that has originated since the Global Financial Crisis, the "Great Recession", more recently, the COVID-19 outbreak (see, David and Veronesi (2022) for a detailed review).

[1] The Paris Agreement has a long-term temperature goal which is to keep the rise in global surface temperature to well below 2 °C (3.6 °F) above pre-industrial levels. The treaty also states that preferably the limit of the increase should only be 1.5 °C (2.7 °F), and to stay below 1.5 °C of global warming, emissions need to be cut by roughly 50% by 2030.

The remainder of the paper is organized as follows: Section 2 presents the data and basics of the econometric framework, while Section 3 discusses the results, and Section 4 concludes.

2. Data and Methodology

Fuchs et al. (2024) derive the Carbon VIX by constructing a portfolio of EUA options, with portfolio weights chosen to ensure that the payoff at option expiry approximates the realized variance of EUA futures until option's expiry. When the expected EUA price variance rises, which corresponds to periods of higher carbon price uncertainty, the price of this portfolio rises. As the VIX methodology targets expected volatility rather than variance, the Carbon VIX is computed as the square-root of the portfolio price. In contrast, the CIV is derived directly from the implied volatilities of EUA options. The implied volatility of a specific option represents the level of volatility in the underlying returns of the asset that produces the current market price of that option, when used as an input in an option pricing model. All else being equal, a higher option price corresponds to a higher implied volatility. The data on both Carbon VIX and CIV are available at https://www.carbonvix.org/, and covers the period of 1^{st} week (7^{th}) of September 2013 to the 4^{th} week (31^{st}) of December 2022. Figure 1 plots the Carbon VIX and the CIV data. The two series depict close cyclical comovements, with the mean and volatilities of these two indexes coming down significantly during the peak of the COVID-19 pandemic, but to only pick-up again since the end of 2021 (though not to pre-coronavirus levels) when economic activities started to recover.

In terms of the econometric model, we rely on fractional integration, which is known to be a more flexible approach in comparison with classical methods based on stationarity or unit root tests. Formally, the model is given as follows:

$$y(t) \;=\; \alpha \;+\; x(t), \qquad (1-B)^d\, x(t) \;=\; u(t), \qquad t \;=\; 1, 2, \ldots \tag{1}$$

where $y(t)$ is the observed time series of Carbon VIX or CIV, considered either in original, i.e., raw, or log-form; α is an unknown parameter related with the intercept; $x(t)$ is supposed to be $I(d)$ where d is a real value; B is the backshift operator, and; $u(t)$ is $I(0)$. With respect to this latter component, we make two assumptions: (i) $u(t)$ is uncorrelated with zero mean and constant variance, and; (ii) $u(t)$ may exhibit serial correlation, which we model using a non-parametric approach proposed by Bloomfield (1973). This method approximates Autoregressive (AR) structures while avoiding the need to specify a parametric AR model explicitly. The estimation of the degree of fractional integration, d, is conducted via the tests outlined in Robinson (1994). This approach allows us to obtain the point estimates of d along with the 95% confidence bands that identify the range of its non-rejection values .

3. Empirical findings

Table 1 displays the estimates of d for the original data, i.e., raw data under the assumptions of no and weak autocorrelation in the upper panel, and the same set under logged values in the lower panel. For both Carbon VIX and CIV the null of unit root hypothesis, i.e., I(1) behavior cannot be rejected given the assumption of zero autocorrelation in the error structure irrespective of whether we look at raw or logged data. However, when we impose the assumption of weak autocorrelation, the orders of integration in both non-transformed and logged data are now much smaller, with mean reversion (d<1) long-memory (covariance nonstationary) process observed in both scenarios. It must be pointed out that the estimate of d for Carbon VIX and CIV are quite similar in magnitude to each other.

As can be seen from Table 1, the estimate of d, suggesting unit root process for Carbon VIX and CIV, is unaffected whether we use raw data or logarithmic transformation. But, when we assume an autocorrelated error structure, Carbon VIX and CIV both tend to be mean-reverting.[2] Given this, the results for the recursive estimation of d (along with the 95% lower (LB) and upper (UB) confidence bands), done every four weeks, presented in Figure 1 over the period of 19th December 2015 to 31st December 2022, is based on the original untransformed data but with the error structure of the fractional integration model (Equation (1)) characterized by weak autocorrelation.

[INSERT TABLE 1 HERE]

Figure 1 presents the time-varying (recursive) estimates of the persistence parameter, d, for both the Carbon VIX (Panel a) and CIV (Panel b) over the period from December 2015 to December 2022, with 95% confidence intervals. These recursive estimates offer insights into how the persistence of carbon price uncertainty evolved throughout this period. A sharp decline in the persistence of Carbon VIX is observed around the 3rd week of November 2018, while a similar drop in the persistence of CIV occurs during the 1st week of April 2020. Following these points, both measures show a general downward trend in persistence, indicating that the impact of shocks to carbon price uncertainty became less enduring over time.

This decline in persistence suggests that carbon price uncertainty, initially characterized by long-lasting effects, now dissipates more quickly, signaling improved stability. The reduced persistence can be intuitively attributed to improvements in the transparency and consistency of regulatory updates within the EU Emissions Trading System (EU-ETS). Clear communication and predictable policy changes regarding the supply and allocation

[2] As a matter of comparison, we also estimated the long-memory parameter, d, of the untransformed volatility index data associated with the Euro Stoxx 50 (VSTOXX), under the assumption of autocorrelation in the error structure. The estimate of d over the same sample period as the two metrics of carbon price uncertainty was found to be relatively smaller at 0.63, with the 95% confidence band of (0.50, 0.78). This observation is in line with that of Fuchs et al. (2024), who found the first-order autoregressive coefficient of the changes in Carbon VIX and the CIV to be higher than the same for the changes in the VIX of the S&P 500. Note that the daily data for the VSTOXX was downloaded from: https://www.stoxx.com/data-index-details?symbol=V2TX, and converted to weekly frequency based on systematic sampling, i.e., using the observation for the last day of a particular week as the associated weekly value. Interestingly, the estimate of d (95% confidence band) for raw carbon price (also sourced from Fuchs et al. (2024)) with autocorrelated error structure, in line with the earlier work of Gil-Alana et al. (2016), was 0.86 (0.80, 0.95), i.e., higher than both Carbon VIX and CIV. In addition, as a matter of comparability, Generalized Autoregressive Conditional Heteroskedasticity (GARCH) model-based conditional volatility fitted to the log-returns of carbon price, just like the Carbon VIX and CIV depicted mean-reversion with long-memory given a value of d (95% confidence band) = 0.59 (0.42, 0.77), when we used the raw data and allowed for autocorrelation in the error process. Finally, under the same model-set-up, the estimates of d (95% confidence band) for the changes and the cumulated sum of the expected decarbonisation investment, as derived by Fuchs et al. (2024), was found to be 0.03 (-0.04, 0.18) and 1.05 (0.96, 1.12), respectively. In some sense, as the underlying variable measuring the decarbonisation investment involves stock returns of firms that act as carbon solution providers, we can say that these equity prices, not surprisingly, reflect the weak-form of the Efficient Market Hypothesis (EMH).

of emission allowances likely reduced market uncertainty, creating a more stable environment and enhancing the effectiveness of the EU-ETS.

[INSERT FIGURE 1 HERE]

To econometrically validate our claim, we ran ordinary least squares (OLS) regressions, whereby we regressed the time-varying persistence parameter estimates for Carbon VIX or CIV on a constant, and a metric of carbon policy uncertainty (*CPU*), following the approach of Scotti et al. (2016) and Känzig (2023). Understandably, our hypothesis is that the response of the evolving persistence of Carbon VIX and CIV to *CPU* should be positively related, particularly since the start of declining trends of the time-varying estimates of *d*.

The steps followed to create the *CPU* measure as follows: First, we identify daily carbon policy surprises (*CPS*) from changes in the European Union Allowances (EUA) futures prices in tight window around four types of regulatory events, identified by Degasperi et al. (2024),[3] concerning the overall cap in the EU-ETS, the free allocation of allowances, the auctioning of allowances, and the use of international credits. Formally, $CPS_{t,d} = (F_{t,d}-F_{t,d-1})/P_{t,d-1}$, where where $F_{t,d}$ ($F_{t,d-1}$) is settlement price of the EUA front contract on event day *d* (*d-1*) in week *t*, and $P_{t,d-1}$ is the wholesale electricity price on the day before. We obtain $CPS_{t,d}$ for futures contract ranging from 1 to 12 months. The data on the prices are sourced from the Bloomberg terminal. In the second step, we square the 12 *CPS* series, standardize them and obtain the first principal component as the $CPU_{t,d}$. Finally, to match our weekly time-varying persistence of Carbon VIX and CIV, we convert the daily $CPU_{t,d}$ to weekly $CPU_{t,w}$, which we denote simply as *CPU*, by summing the daily values over a week to account for possible multiple events. The $CPU_{t,w}$ has been plotted in Figure 2, over the full-sample period of 7th of September 2013 to 31st of December 2022. As can be seen, there were frequent peaks of carbon policy-related uncertainties between the November of 2018 to the November of 2020 associated with regulatory event updates, but has ever since started to taper off.

[INSERT FIGURE 2 HERE]

Reverting back to our regression analyses, over the period of 19th December 2015 to 31st December 2022, the coefficient estimate (*p*-value) corresponding to the *CPU* variable in the persistence parameter equations of the Carbon VIX and CIV were found to be -0.0002 (0.1416) and -0.0002 (0.5335) respectively, with both being statistically insignificant (using Heteroskedasticity and Autocorrelation (HAC)-adjusted Newey and West (1987) standard errors). In other words, we fail to detect evidence in favor of our hypothesis. However, when we analyzed the sub-samples beginning on the 3rd week of November 2018 for Carbon VIX and on the 1st week of April 2020 for CIV, the corresponding estimates (*p*-value) were found to be equal to 0.002 (0.0035) and 0.0001 (0.0418). Evidently, persistence of Carbon VIX and CIV is positively impacted by uncertainty associated with regulation event updates, as captured by the *CPU*. In sum, our results indicate that during these critical periods, regulatory updates had a noticeable impact on the persistence of carbon price uncertainty. As the CPU increased during periods of regulatory uncertainty, the persistence of both the Carbon VIX and CIV also increased, consistent with the idea that policy-related uncertainty can delay the resolution of price

[3] The reader is referred to Table of A1 of Degasperi et al. (2024) for complete details of the 85 events over our sample period.

uncertainty. Hence, our analysis highlights the importance of effective policy communication and regulatory stability in reducing uncertainty in carbon markets.

4. Conclusion

This paper provides empirical evidence on the persistence of carbon price uncertainty using two high-frequency measures: the Carbon VIX (CVIX) and Carbon Implied Volatility (CIV). Utilizing fractional integration models, we analyze the persistence of these metrics over the period from September 2013 to December 2022, with a focus on understanding how regulatory interventions influence the time-varying nature of carbon price uncertainty. While our findings suggest that both metrics exhibit mean-reversion with long-memory processes, indicating that uncertainty persists for some time but eventually dissipates, the recursive analysis reveals a declining trend in persistence over recent years.

The decline in persistence aligns with improvements in the transparency and consistency of regulatory updates within the EU Emissions Trading System (EU-ETS). Using our newly developed Carbon Policy Uncertainty (CPU) index, which aggregates squared carbon policy surprises over different maturities of EUA futures contracts, we find that effective regulatory communication has played a key role in reducing the persistence of carbon price uncertainty. Specifically, after significant regulatory events in November 2018 and April 2020, the persistence of both the Carbon VIX and CIV declined, highlighting the importance of clear and predictable policies.

From a policy perspective, these findings offer several important implications. First, the results emphasize the need for regulatory consistency and clear communication to maintain low levels of carbon price uncertainty.[4] Policymakers should focus on minimizing abrupt or unexpected changes to the rules governing carbon markets, as uncertainty in carbon pricing can delay investments in decarbonization, hindering progress toward emission reduction targets. Second, while the post-COVID-19 recovery has witnessed fluctuations in carbon price uncertainty, the reduced persistence in the Carbon VIX and CIV suggests that recent increases in uncertainty are likely to dissipate faster than in the past. This reinforces the value of proactive regulatory measures that stabilize market expectations.

Future research could explore the spillover effects of carbon price uncertainty on other financial markets, such as energy commodities, equity markets, and green bonds, to understand how volatility in carbon markets influences broader investment behavior. Additionally, further work could investigate the role of regional differences in carbon pricing schemes—for example, comparing the persistence of carbon price uncertainty in the EU-ETS with other emerging carbon markets, such as those in China or North America.

[4] This is more so, since the VSTOXX has become highly connected with Carbon VIX and CIV, with the carbon price uncertainties being net-receivers of financial uncertainty post COVID-19, as revealed by time-varying spillover analysis, presented in Figure A1 in the Appendix of the paper. Note that these findings were derived from the connectedness approach of Antonakakis et al. (2020), based on Time-Varying Parameter-Vector Autoregressive (TVP-VAR) models, estimated with lag-order of 2, chosen using the Schwarz information criterion (SIC). Furthermore, based on time-varying generalized impulse responses (not reported here), we found a positive shock to VSTOXX increased Carbon VIX and CIV as well over the entire sample period, with the peak effect during COVID-19, thus suggesting a positive relationship running from financial uncertainty to carbon price uncertainties.

References

Abakah, E.J.A. Caporale, G.M., Gil-Alana, L.A. (2021). Economic policy uncertainty: Persistence and cross-country linkages. Research in International Business and Finance, 58,101442.

Antonakakis, N., Chatziantoniou, I., and Gabauer, D. (2020). Refined Measures of Dynamic Connectedness based on Time-Varying Parameter Vector Autoregressions. Journal of Risk and Financial Management, 13(4), 1-23.

Bloom, N. (2009). The impact of uncertainty shocks. Econometrica, 77(3), 623-685.

Bloomfield, P. (1973). An exponential model in the spectrum of a scalar time series. Biometrika, 60(2), 217-226.

David, A, and Veronesi, P. (2022). A Survey of Alternative Measures of Macroeconomic Uncertainty: Which Measures Forecast Real Variables and Explain Fluctuations in Asset Volatilities Better? Annual Review of Financial Economics, 14, 439-463.

Degasperi, R., Natoli, F., and Pallara, K. (2024. The Macroeconomic Effects of the Green Transition. Available at SSRN: https://ssrn.com/abstract=4930140.

Fuchs, M., Stroebel, J., and Terstegge, J. (2024). Carbon VIX: Carbon Price Uncertainty and Decarbonization Investments. National Bureau of Economic Research (NBER) Working Paper No. 32937.

Gil-Alana, L.A., Gupta, R., and de Gracia, F.P. (2016). Modeling persistence of carbon emission allowance prices. Renewable and Sustainable Energy Reviews, 55, 221-226.

Gil-Alana, L.A., and Payne, J.E. (2020). Measuring the degree of persistence in the U.S. economic policy uncertainty index. Applied Economics Letters, 27(10), 831-835.

Känzig, D.R. (2023). The Unequal Economic Consequences of Carbon Pricing. National Bureau of Economic Research (NBER) Working Paper No. 31221.

Newey, W.K., and West, K.D. (1987). A Simple, Positive Semi-definite, Heteroscedasticity and Autocorrelation Consistent Covariance Matrix. Econometrica, 55(3), 703-708.

Plakandaras, V., Gupta, R., and Wohar, M.E. (2019). Persistence of economic uncertainty: A comprehensive analysis. Applied Economics, 51(41), 4477-4498.

Robinson, P.M. (1994). Efficient tests of nonstationary hypotheses. Journal of the American Statistical Association, 89(428), 1420-1437.

Scotti, C. (2016). Surprise and Uncertainty Indexes: Real-Time Aggregation of Real-Activity Macro Surprises. Journal of Monetary Economics, 82, 1-19.

Solarin, S.A., and Gil-Alana, L.A. (2021). The persistence of economic policy uncertainty: Evidence of long range dependence. Physica A: Statistical Mechanics and its Applications, 568, 125698.

Sheng, X., Gupta, R., and Cepni, O. (2022). Persistence of State-Level Uncertainty of the United States: The Role of Climate Risks. Economics Letters, 215, 110500.

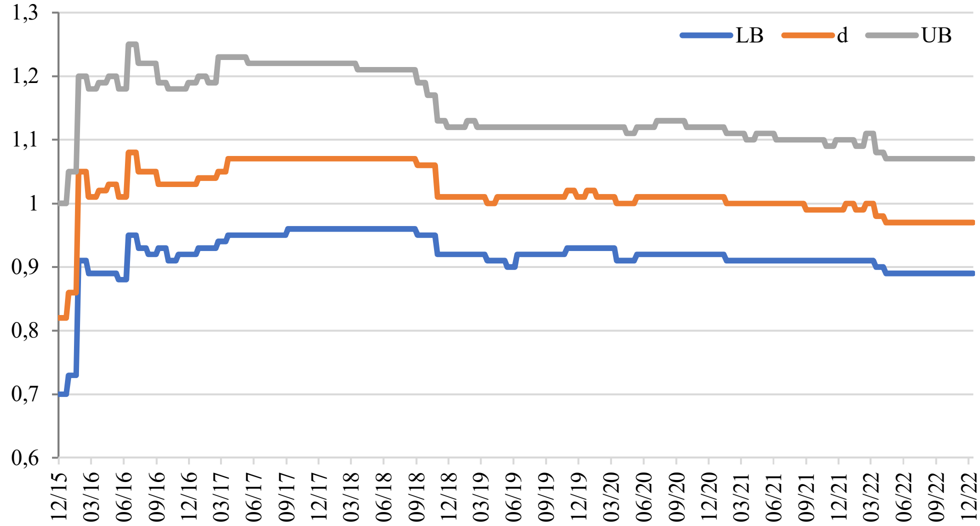
Table 1. Estimated order of integration for carbon price uncertainty series

	ORIGINAL (RAW) DATA			
	i) No autocorrelation		ii) Weak autocorrelation	
Series	d (95% band)	α (t-stat)	d (95% band)	α (t-stat)
Carbon VIX	0.97 (0.89, 1.07)	68.827 (20.47)	**0.78 (0.68, 0.91)**	68.686 (21.94)
CIV	0.96 (0.88, 1.05)	67.076 (18.92)	**0.79 (0.68, 0.93)**	67.213 (20.13)
	LOGGED TRANSFORMED DATA			
	i) No autocorrelation		ii) Weak autocorrelation	
Series	d (95% band)	α (t-stat)	d (95% band)	α (t-stat)
Carbon VIX	1.02 (0.94, 1.12)	4.229 (72.97)	**0.81 (0.71, 0.95)**	4.231 (76.88)
CIV	1.02 (0.94, 1.11)	4.202 (66.66)	**0.83 (0.72, 0.98)**	4.207 (69.48)

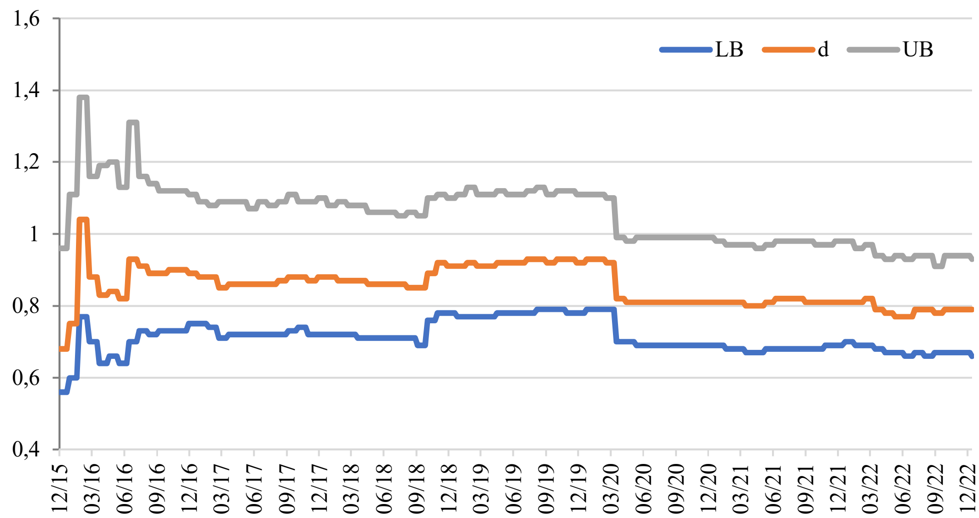
Note: Bold entries indicate evidence of mean reversion at the 95% level.

Figure 1. Time-varying (recursive) estimate of the long-memory parameter (d)

(a). Carbon VIX

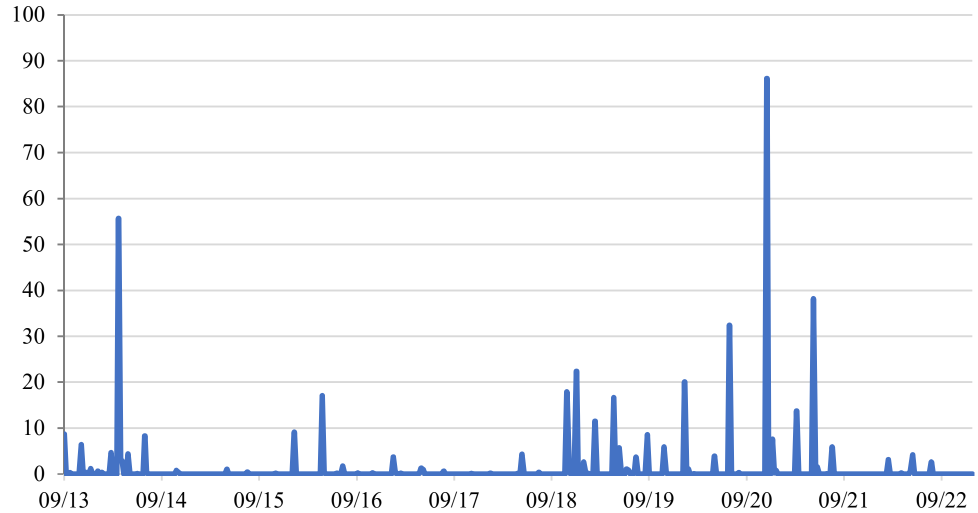


(b). CIV



Note: LB and UB are 95% lower and upper confidence bands.

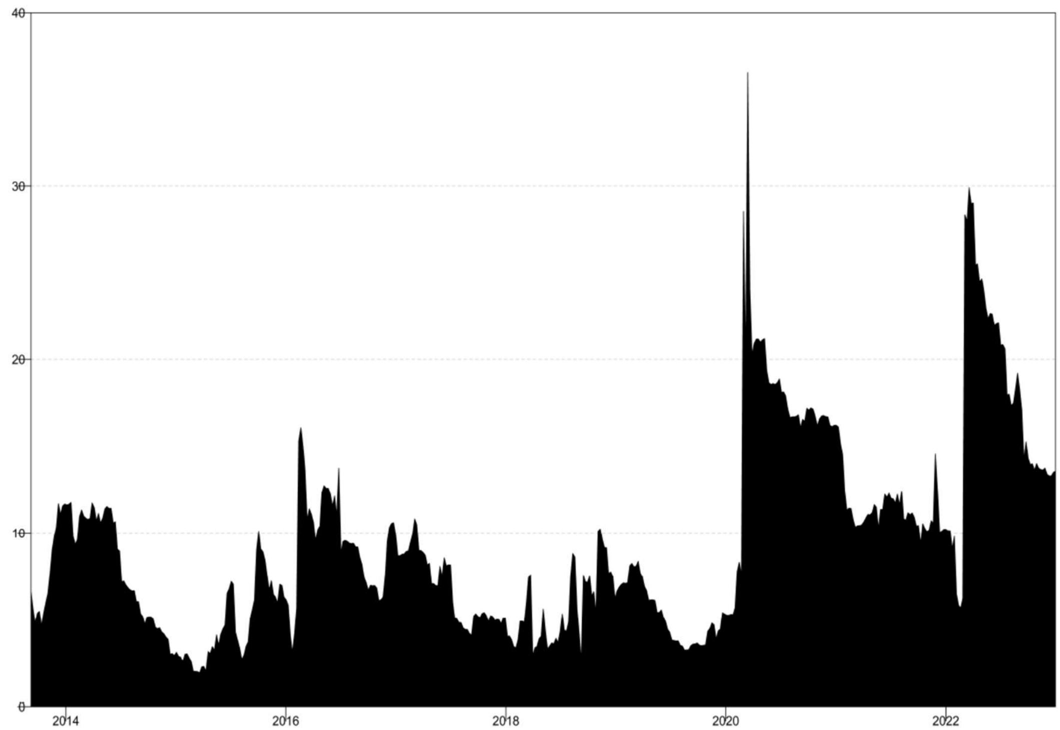
Figure 2. Carbon Policy Uncertainty (*CPU*)



APPENDIX:

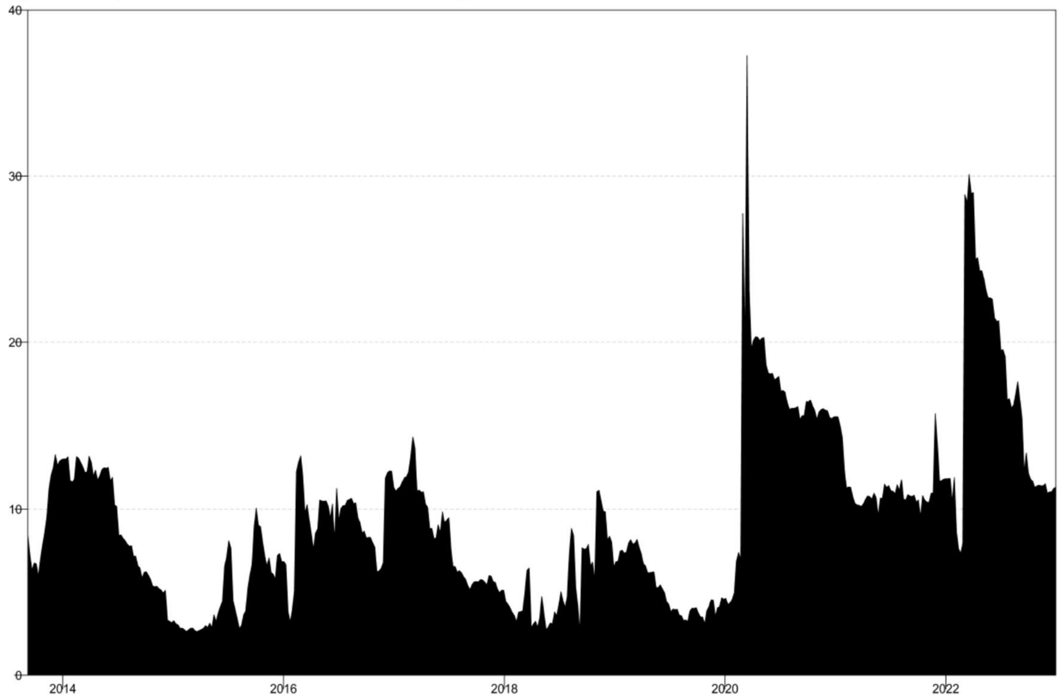
Figure A1. Time-varying spillover results between Carbon VIX and VSTOXX, and Carbon Implied Volatility (CIV) and VSTOXX

(a). Dynamic total connectedness for Carbon VIX-VSTOXX



(b). Net pairwise connectedness for Carbon VIX-VSTOXX

(c). Dynamic total connectedness for CIV-VSTOXX



(d). Net pairwise connectedness for CIV-VSTOXX