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Time-variation in the persistence of carbon price uncertainty: The role of carbon policy uncertainty☆

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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 reduction in persistence of carbon price uncertainties is a result of declining carbon policy uncertainty — a metric 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).

1. Introduction

Understanding both the persistence and impact of carbon price uncertainty is critical within the broader context of global policy efforts aimed at mitigating climate change. Such uncertainty notably influences corporate behavior, particularly affecting companies' willingness and readiness to commit to long-term investments in emission reduction, and global decarbonization initiatives. Fuchs et al. (2024) analyze how carbon price uncertainty affects corporate investment decisions by introducing two indicators—Carbon Volatility Index (CVIX) and Carbon Implied Volatility (CIV). Their research shows that increased CVIX and CIV levels are associated with lower stock returns for carbon solution firms and postponed decarbonization investments, consistent with the theory of real options under uncertainty (Bloom, 2009).[1] Importantly, the persistence of carbon price uncertainty significantly extends the time for its impacts to fade. This prolonged uncertainty could negatively affect decarbonization efforts, impeding progress toward global climate goals.

To further investigate this, we apply fractional integration models to estimate the persistence of carbon price uncertainty using the CVIX and CIV indicators developed by Fuchs et al. (2024), covering the period from the first week of September 2013 to the fourth week of December 2022. In addition to analyzing the complete sample, we employ recursive econometric modeling starting from the third week of December 2015—a timeframe beginning shortly after the drafting of the Paris Agreement.[2] This approach allows us to examine evolving patterns in the persistence of carbon price uncertainty. The recursive (time-varying) estimation method, which highlights trends in persistence, provides

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[1] Ren et al. (2023), using the Chinese stock market as an example, show that carbon price uncertainty can increase the possibility of crash risk.

[2] See: https://www.un.org/en/climatechange/paris-agreement.

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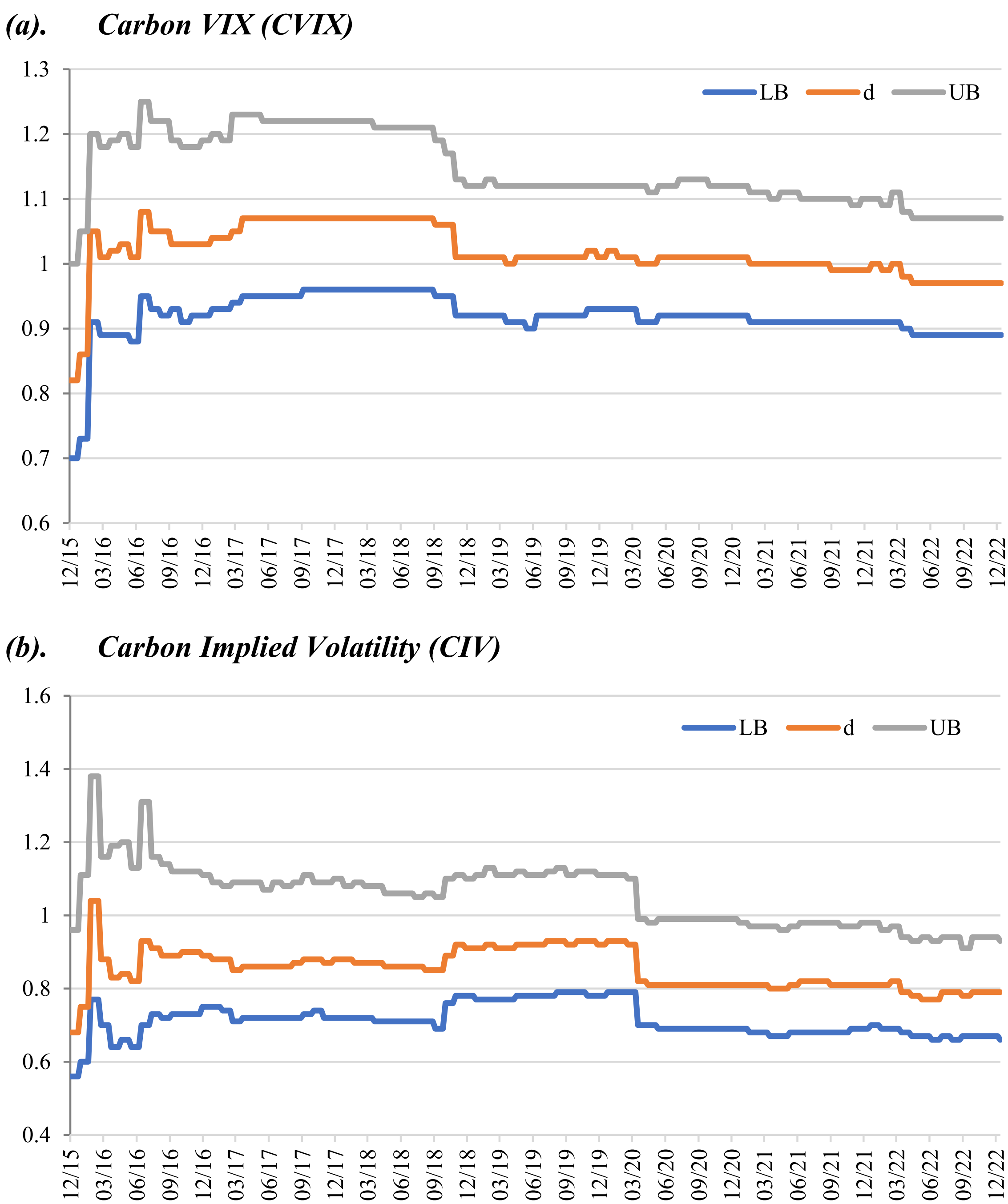

Fig. 1. Time-varying (recursive) estimate of the long-memory parameter (d). Note: The model is $y(t) = \alpha + x(t)$, $(1 - B)^d x(t) = u(t)$, $t = 1, 2, \ldots$,where $y(t)$ is untransformed CVIX or CIV; α is the intercept; $x(t)$ is assumed to be $I(d)$ where d is a real value; B is the backshift operator, and; $u(t)$ is $I(0)$; with $u(t)$ exhibiting serial correlation as per Bloomfield (1973). The figure plots the recursive estimation of d, done every four weeks over the period of 19th December 2015–31 st December 2022, and is based on tests in Robinson (1994). LB and UB are 95 % lower and upper confidence bands corresponding to the time-varying estimation of d.

policymakers with valuable insights, to assess the necessary level of intervention to effectively manage and reduce uncertainty in carbon pricing.

To our knowledge, this is the first study to specifically analyze the persistence of carbon price uncertainty within the European Union Emissions Trading System (EU-ETS). Moreover, we pioneer efforts to explain trends in persistence by introducing a novel measure of uncertainty specifically linked to carbon pricing policies. By doing so, we contribute to existing literature that has identified significant levels of persistence or long-memory characteristics in various macroeconomic and financial uncertainties. Previous research has predominantly employed fractional integration models to study uncertainties at global and regional macroeconomic and financial levels (e.g., Abakah et al., 2021; Gil-Alana & Payne, 2020; Plakandaras et al., 2019; Solarin & Gil-Alana, 2021; Sheng et al., 2022). Additionally, by developing an uncertainty metric directly tied to carbon pricing policies, we extend the substantial body of literature on policy-related uncertainty measures that emerged following the Global Financial Crisis, the "Great Recession, " and more recently, the COVID-19 pandemic (see David and Veronesi 2022 for a detailed overview).

Our results indicate that both CVIX and CIV exhibit long-memory behavior with mean reversion. Additionally, recursive estimation

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

	Untransformed data			
	i) No autocorrelation		ii) Weak autocorrelation	
Series	d (95 % band)	α (t-stat)	d (95 % band)	α (t-stat)
CVIX	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)
CVIX	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: The model estimated over the full-sample (1st week of September 2013 to the 4th week of December 2022) is: $y(t) = \alpha + x(t)$, $(1 - B)^d x(t) = u(t)$, $t = 1, 2, \ldots$,where $y(t)$ is Carbon VIX (CVIX) or Carbon Implied Volatility (CIV); α is 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 $u(t)$ being either uncorrelated with zero mean and constant variance, or $u(t)$ exhibits serial correlation as per Bloomfield (1973). The estimation of d, along with the 95 % confidence bands, is based on tests in Robinson (1994). Bold entries indicate evidence of mean reversion at the 95 % level of significance.

highlights a downward trend in persistence, driven primarily by recent reductions in carbon price policy uncertainty. These findings underline the importance of regulatory consistency and clear policy communication. Policymakers should thus prioritize minimizing abrupt or unexpected changes in carbon market regulations, as heightened uncertainty can delay crucial investments in decarbonization, thereby impeding progress toward emissions reduction targets. Furthermore, despite fluctuations in carbon price uncertainty following the COVID-19 recovery period, the decreasing persistence observed in CVIX and CIV suggests that recent surges in uncertainty may dissipate more rapidly than previously experienced, reinforcing the value of proactive measures to stabilize expectations in carbon markets.

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.

1.1. Data and methodology

Fuchs et al. (2024) introduce the CVIX by constructing a portfolio of European Union Allowances (EUA) options weighted to approximate the realized variance of EUA futures at option expiry. An increase in expected EUA price variance, indicating higher carbon price uncertainty, leads to a rise in this portfolio's price. Since VIX methodology targets expected volatility, the CVIX is calculated as the square root of this portfolio price. In contrast, the CIV is directly derived from the implied volatilities of EUA options. Implied volatility reflects the asset's underlying volatility required to match the observed market price of an option, where higher option prices correspond to higher implied volatilities.

Both CVIX and CIV data are available at: https://www.carbonvix.org/ for the period from the first week of September 2013 to the fourth week of December 2022, totaling 493 weekly observations. Fig. 1 illustrates that the two series exhibit closely aligned cyclical movements. Notably, the mean and volatility of both indices significantly decreased during the peak of the COVID-19 pandemic, recovering partially after late 2021, although not fully returning to pre-pandemic levels.

Econometrically, our analysis utilizes fractional integration, a flexible alternative to classical methods relying on stationarity or unit root tests. The fractional integration model is formally expressed as:

$$y(t) = \alpha + x(t),\ (1 - B)^d x(t) = u(t),\ t = 1, 2, \quad (1)$$

Here, $y(t)$ represents the observed CVIX or CIV series, either in original or log-transformed form; α is the intercept parameter; $x(t)$ is assumed to be fractionally integrated, denoted by I(d), where d is a real number; B is the backshift operator; and $u(t)$ is a stationary process, I(0). We assume $u(t)$ is uncorrelated with zero mean and constant variance, potentially exhibiting serial correlation approximated using Bloomfield's (1973) non-parametric method. This approach effectively captures autoregressive structures without explicitly specifying an AR model. The fractional integration parameter, d, is estimated following Robinson's (1994) procedure, providing point estimates along with 95 % confidence intervals indicating the range of non-rejection values.

2. Empirical findings

Table 1 presents estimates of the parameter d for both untransformed and logged data. The upper panel reports results under the assumptions of no and weak autocorrelation for the untransformed data, while the lower panel provides analogous results for logged values. Under the assumption of zero autocorrelation in the error structure, the unit root hypothesis (I(1) behavior) cannot be rejected for either CVIX or CIV, regardless of whether the data is examined in levels or log form. However, when assuming weak autocorrelation, estimates for d decrease significantly for both untransformed and logged data, indicating mean-reverting ($d < 1$) long-memory (covariance nonstationary) behavior in both cases. The estimated values of d for CVIX and CIV are remarkably similar in magnitude.

For comparability, the conditional volatility derived from the Generalized Autoregressive Conditional Heteroskedasticity (GARCH) model fitted to log-returns of carbon price[3] data (from Fuchs et al., 2024) also displays mean-reversion with long-memory, showing an estimated d value (95 % confidence band) of 0.59 (0.42, 0.77).[4]

Fig. 1 illustrates recursive estimates of the persistence parameter d for CVIX (Panel a) and CIV (Panel b) from December 2015 to December 2022, computed at four-week intervals using untransformed data under the assumption of weak autocorrelation. A notable decline in persistence occurs around the third week of November 2018 for CVIX and in the first week of April 2020 for CIV. After these points, a general downward trend in persistence emerges, indicating diminishing long-lasting impacts of shocks on carbon price uncertainty, likely due to improved regulatory transparency and consistency in the EU Emissions Trading System (EU-ETS).

To empirically validate this observation, we estimate ordinary least squares (OLS) regressions, regressing time-varying persistence estimates for CVIX and CIV against a carbon policy uncertainty metric derived following Scotti (2016) and Känzig (2023). The carbon policy uncertainty measure (CPU) was constructed by identifying daily carbon policy surprises (CPS) from changes in EUA futures prices surrounding specific regulatory events. Complete event details are provided in Table 2.

The process for creating the CPU measure involved several steps. First, we calculated the daily CPS by examining changes in EUA futures prices closely around four specific regulatory events affecting the EU-ETS system. These events included changes to the overall emissions cap, the free allocation, auctioning of allowances, and the use of international credits, as detailed by Degasperi et al. (2024). The CPS formula used is: $CPS_{t,d} = (F_{t,d} - F_{t,d-1})/P_{t,d-1}$, where $F_{t,d}$ ($F_{t,d-1}$) represent the

[3] Interestingly, the estimated d for untransformed carbon price was 0.86 (95 % CI: 0.80, 0.95), higher than for both CVIX and CIV, consistent with Gil-Alana et al. (2016).

[4] As an additional analysis of carbon market dynamics, we estimated d for both the changes and cumulative sum of expected decarbonisation investment (derived from Fuchs et al., 2024). These estimates were 0.03 (-0.04, 0.18) and 1.05 (0.96, 1.12), respectively. Since the underlying variable reflects stock returns of carbon solution firms, the results unsurprisingly align with the weak-form Efficient Market Hypothesis (EMH).

Table 2
List of regulatory events over 7th of september 2013–31 st of December 2022.

Date	Event No.	Event description
26/09/2013	1	Update on number of aviation allowances to be auctioned in 2012
08/11/2013	2	Member states endorsed negotiations on the back-loading proposal
21/11/2013	3	Commission submitted non-paper on back-loading to the EU Climate Change Committee
10/12/2013	4	European Parliament voted for the back-loading proposal
11/12/2013	5	Climate Change Committee makes progress on implementation of the back-loading proposal
18/12/2013	6	Commission gives green light for a first set of member states to allocate allowances for calendar year 2013
08/01/2014	7	Climate Change Committee agrees back-loading
22/01/2014	8	Commission proposed to establish a market stability reserve for phase V
26/02/2014	9	Commission gives green light for free allocation by all member states
27/02/2014	10	Back-loading: 2014 auction volume reduced by 400 million allowances
13/03/2014	11	Commission approves first batch of international credit entitlement tables
28/03/2014	12	Commission approves second batch of international credit entitlement tables
04/04/2014	13	Update on approval of international credit entitlement tables
11/04/2014	14	Commission approves four more international credit entitlement tables
23/04/2014	15	Commission approves final international credit entitlement tables
02/05/2014	16	Commission published the number of international credits exchanged
05/05/2014	17	Commission submits proposed carbon leakage list for 2015–2019
04/06/2014	18	Auctioning of aviation allowances to restart in September
04/07/2014	19	Commission published the first update on the allocation of allowances from the New Entrants' Reserve
09/07/2014	20	Climate Change Committee agrees proposed carbon leakage list for the period 2015–2019
27/10/2014	21	Commission adopts the carbon leakage list for the period 2015–2019
04/11/2014	22	Updated information on exchange and international credit use
04/05/2015	23	Updated information on exchange and international credit use
15/07/2015	24	Proposal to revise the EU emissions trading system for the period after 2020
23/07/2015	25	Commission publishes status update for New Entrants' Reserve and allocation reductions
04/11/2015	26	Updated information on exchange and international credit use
15/01/2016	27	Commission publishes status update for New Entrants' Reserve
28/04/2016	28	Court judgment on free allocation in the EU ETS for the period 2013–2020
02/05/2016	29	Updated information on exchange and international credit use
23/06/2016	30	Following court judgement, commission to modify cross-sectoral correction factor for 2018–2020
15/07/2016	31	Commission published a status update on the allocation of allowances from the New Entrants' Reserve 2013–2020
08/09/2016	32	Court judgment on free allocation in the EU ETS for the period 2013–2020
04/11/2016	33	Updated information on exchange and international credit use
16/01/2017	34	Commission publishes status update for New Entrants' Reserve
24/01/2017	35	Commission adopts Decision to implement Court ruling on the cross-sectoral correction factor
15/02/2017	36	European Parliament voted in support of the revision of the ETS Directive for the period after 2021

(*continued on next page*)

Table 2 (*continued*)

Date	Event No.	Event description
27/04/2017	37	Climate Change Committee approves technical changes to auction rules
02/05/2017	38	Updated information on exchange and international credit use
12/05/2017	39	Commission publishes first surplus indicator for ETS Market Stability Reserve
17/07/2017	40	Commission publishes status update for New Entrants' Reserve
26/07/2017	41	Court judgment again confirms benchmarks for free allocation of ETS allowances for 2013–2020
06/11/2017	42	Updated information on exchange and international credit use
15/01/2018	43	Commission publishes status update for New Entrants' Reserve
04/05/2018	44	Updated information on exchange and international credit use
08/05/2018	45	Commission Notice on the preliminary carbon leakage list for phase IV (2021–2030)
15/05/2018	46	ETS Market Stability Reserve will start by reducing auction volume by almost 265 million allowances
16/07/2018	47	Commission publishes status update for New Entrants' Reserve
30/10/2018	48	Commission adopts amendment to ETS auctioning regulation
06/11/2018	49	Updated information on exchange and international credit use
05/12/2018	50	Poland's 2019 auctions to include some allowances not used for power sector modernization
04/01/2019	51	Amendment to the ETS auctioning regulation
15/01/2019	52	Commission publishes status update for New Entrants' Reserve
15/02/2019	53	Adoption of the Delegated Decision on the carbon leakage list for 2021–2030
23/04/2019	54	Iceland, Liechtenstein and Norway to start auctions on the common auction platform soon
15/05/2019	55	ETS Market Stability Reserve to reduce auction volume by almost 400 million allowances
16/05/2019	56	Revised 2019 auction calendars including EEA EFTA volumes published
12/06/2019	57	Poland's 2020 auction volume to include allowances not used for power sector modernization
19/06/2019	58	Updated information on exchange and international credit use
11/07/2019	59	2020 and revised 2019 auction calendars of the common auction platform published
15/07/2019	60	Commission publishes status update for New Entrants' Reserve
28/08/2019	61	Commission amends ETS auctioning regulation for phase 4
31/10/2019	62	Commission adopts the Regulation on adjustments to free allocation due to activity level changes
08/11/2019	63	Auctioning regulation amendment for phase 4 of the EU ETS published and to enter into force
15/01/2020	64	Commission published the first update on the allocation of allowances from the New Entrants' Reserve
31/01/2020	65	Lifting the suspension of UK-related processes in the Union Registry of the EU ETS
21/02/2020	66	Auction calendar for the UK published
08/05/2020	67	ETS Market Stability Reserve to reduce auction volume by over 330 million allowances between September 2020 and August 2021 + Updated information on exchange and international credit use in the EU ETS
01/07/2020	68	2020 revised auction calendars published
05/08/2020	69	2020 calendar for transfers of allowances between the EU and Swiss emission trading registries
16/11/2020	70	Commission Decision (EU) 2020/1722 of 16 November 2020 on the Union-wide quantity of allowances to be issued under the EU ETS for 2021
17/11/2020	71	Start of phase 4 of the EU ETS in 2021: adoption of the cap and start of the auctions
27/11/2020	72	Timing of the distribution of free allowances in 2021 + 2021 calendar for transfers of allowances between the EU and Swiss emission trading registries
11/12/2020	73	Further information on the start of phase 4 of the EU ETS in 2021: emission allowances to be issued for aircraft operators and the Market Stability Reserve

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Table 2 (*continued*)

Date	Event No.	Event description
17/12/2020	74	Commission Decision (EU) 2020/2166 of 17 December 2020 on the determination of the Member States' auction shares during the period 2021–2030 of the EU ETS
21/12/2020	75	2021 auction calendars published
12/03/2021	76	Commission Implementing Regulation (EU) 2021/447 of 12 March 2021 determining revised benchmark values for free allocation of emission allowances for the period from 2021 to 2025
12/05/2021	77	ETS Market Stability Reserve to reduce auction volume by over 378 million allowances between September 2021 and August 2022
25/05/2021	78	Updated information on exchange and international credits' use in the EU ETS
29/06/2021	79	Commission publishes the national allocation tables of Member States for EU ETS stationary installations eligible to receive free allocation in the period 2021–2025
22/07/2021	80	Revised 2021 and 2022 auction calendars published
16/02/2022	81	Revised 2022 auction calendar for general allowances published
05/04/2022	82	Amendments adopted by the European Parliament on 5 April 2022 on Decision (EU) 2015/1814 regarding the amount of allowances to be placed in the market stability reserve for the Union greenhouse gas ETS until 2030
12/05/2022	83	ETS Market Stability Reserve to reduce auction volume by over 347 million allowances between September 2022 and August 2023 (update)
19/05/2022	84	Revised 2022 auction calendar for general allowances published
28/07/2022	85	Revised 2022 and 2023 auction calendars published

Note: The information is sourced from Table A1 of Degasperi et al# (2024), and concerns the overall cap in the EU-ETS, the free allocation of allowances, the auctioning of allowances, and the use of international credits.

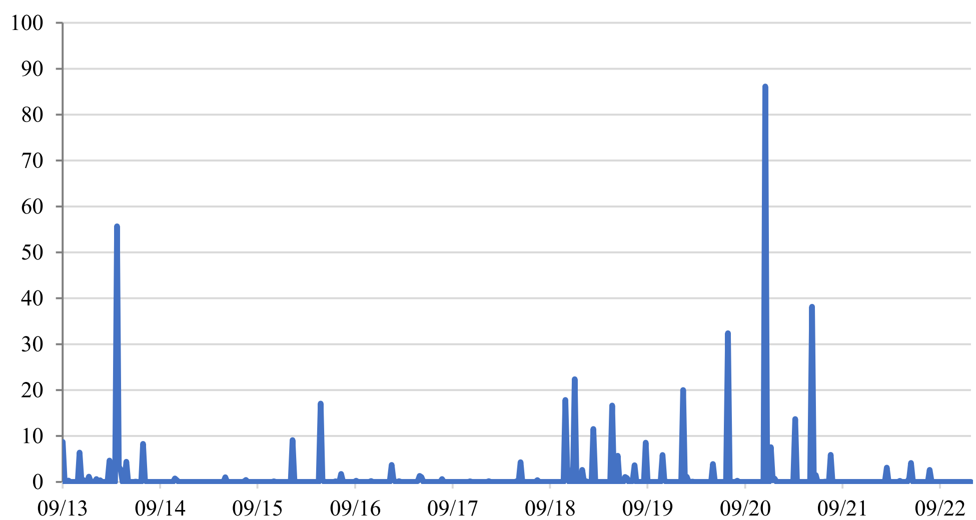

Fig. 2. Carbon Policy Uncertainty (CPU): 7th of September 2013–31 st of December 2022. Note: To get to $CPU_{t,w}$ or CPU: (i) We obtain daily carbon policy surprises (CPS) from changes in the EUA futures prices in tight window around events listed in Table 2, with $CPS_{t,d} = (F_{t,d}\text{-}F_{t,d\text{-}1})/P_{t,d\text{-}1}$, where $F_{t,d}$ ($F_{t,d\text{-}1}$) represent the settlement prices of the EUA front contract on event and previous day, respectively, and $P_{t,d\text{-}1}$ is the prior day's wholesale electricity price; (ii) We obtain $CPS_{t,d}$ for futures contract ranging from 1 to 12 months, with each of the 12 CPS series squared and standardized, and then the first principal component was extracted to create the daily CPU index ($CPU_{t,d}$), and; (iii) we aggregated the daily $CPU_{t,d}$ values into weekly CPU figures ($CPU_{t,w}$) by summing across the week, accommodating multiple events.

settlement prices of the EUA front contract on event and previous day, respectively, and $P_{t,d\text{-}1}$ is the prior day's wholesale electricity price. Second we analyzed CPS data for futures contracts ranging from 1 to 12 months, sourced from Bloomberg. Each of the 12 CPS series was squared, standardized, and then the first principal component was extracted to create the daily CPU index ($CPU_{t,d}$). Finally, to align with the time-varying persistence observed in CVIX and CIV, we aggregated the daily $CPU_{t,d}$ values into weekly figures ($CPU_{t,w}$) by summing across the week, accommodating multiple events.

The resulting weekly CPU data from September 7, 2013, to December 31, 2022, is displayed in Fig. 2. Notably, there were significant peaks in policy-related uncertainty from November 2018 to November 2020 due to updates in regulatory events, detailed in events 49–72 in Table 2. This trend has since shown a decrease.

Regression analysis from December 19, 2015 to December 31, 2022 yielded coefficient estimates (*p*-values) for CPU of −0.0002 (0.1416) for CVIX and −0.0002 (0.5335) for CIV, initially providing limited evidence for our hypothesis. However, in sub-sample analyses post-November 2018 (CVIX) and post-April 2020 (CIV), CPU significantly impacted persistence positively, with estimates of 0.0002 (0.0035) and 0.0001 (0.0418), respectively. These findings confirm that clearer regulatory communications substantially reduced policy uncertainty, subsequently lowering persistence in carbon price uncertainty.

This issue is especially pertinent given the increasing connectivity

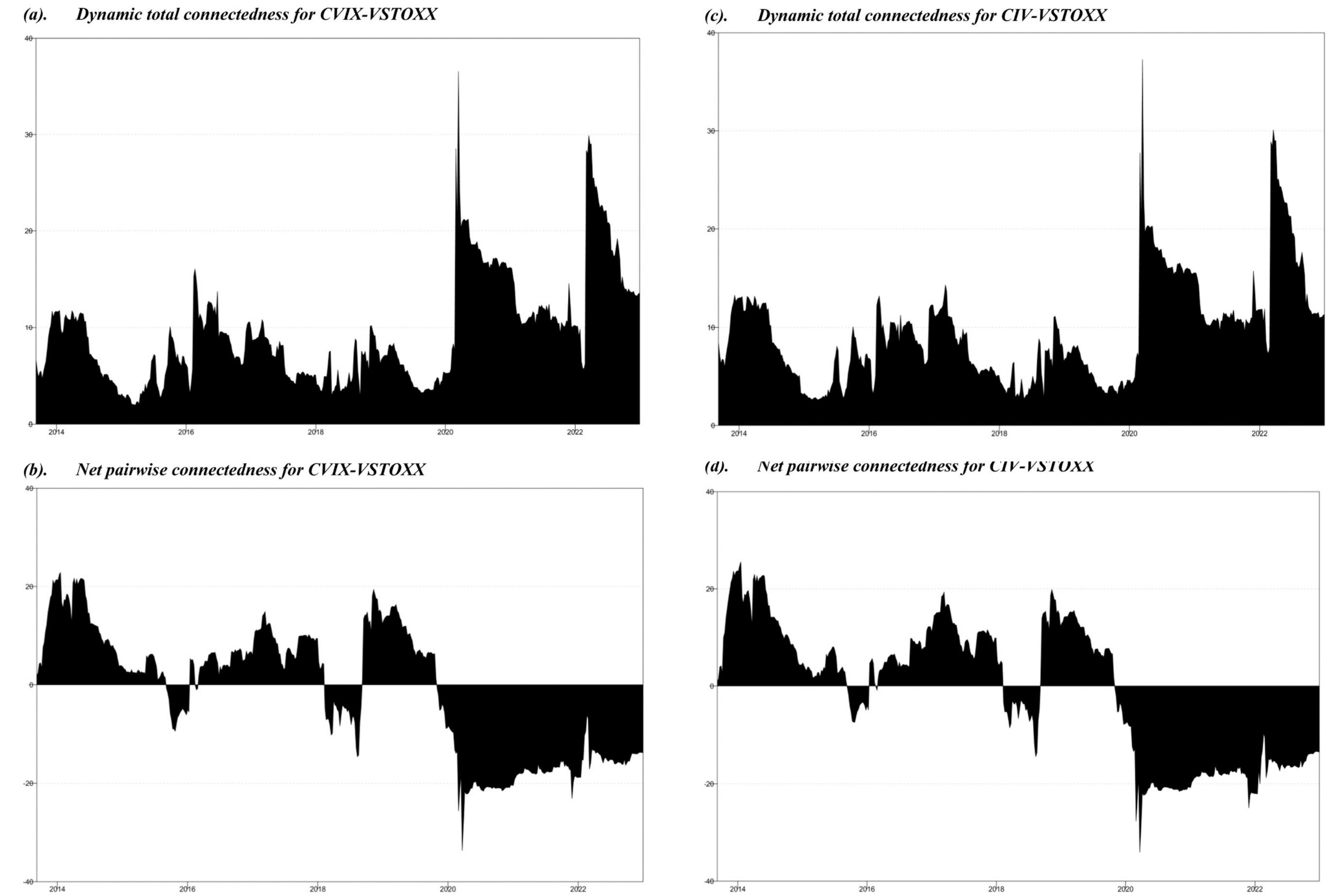

Fig. 3. Time-varying spillover results between Carbon VIX (CVIX) and VSTOXX, and Carbon Implied Volatility (CIV) and VSTOXX. Note: The results of total and net spillovers involving CVIX and VSTOXX, and CIV and VSTOXX, are obtained from TVP-VAR(2) models, based on the estimation method outlined in Antonakakis et al. (2020), to which the reader is referred to for complete technical details. The TVP-VAR models were estimated with a lag-order of 2, chosen using the Schwarz information criterion (SIC).

between financial uncertainty associated with Euro Stoxx 50 (measured by VSTOXX)[5] and carbon price uncertainty, demonstrated by spillover analyses using the Time-Varying Parameter-Vector Autoregressive (TVP-VAR) connectedness methodology (Antonakakis et al., 2020) in Fig. 3.[6] The observed financialization of the carbon market post-COVID-19 suggests that financial market uncertainty—less controllable by policymakers and driven largely by speculative behavior (Chow et al., 2020)—necessitates continued transparent policy communication to manage uncertainty directly within the carbon market.

3. Conclusion

In conclusion, this paper offers empirical evidence on the persistence of carbon price uncertainty, analyzing high-frequency measures—CVIX and CIV—using fractional integration models from September 2013 to December 2022. Our analysis highlights how regulatory clarity and consistency influence the time-varying persistence of carbon price uncertainty, with our findings demonstrating a declining trend in recent years aligned with enhanced regulatory transparency within the EU-ETS. By developing an innovative carbon policy uncertainty index, we reveal a positive association between policy uncertainty and the persistence of CVIX and CIV, particularly since key dates such as November 2018 and April 2020. These insights underline the importance of efficient and transparent regulatory frameworks.

Future research directions include examining spillover effects of carbon price uncertainty into broader financial markets, including energy commodities, equity markets, and green bonds, to better understand cross-market volatility impacts. Additionally, comparative studies exploring regional variations in carbon pricing schemes, such as those in China and North America, would provide valuable context and inform global policy harmonization efforts.

Declaration of Competing Interest

We, the co-authors, of this paper declare that we have no conflict of interest.

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[5] Daily VSTOXX data, converted weekly via systematic sampling, was obtained from https://www.stoxx.com/data-index-details?symbol=V2TX. Its estimated d was 0.63 (95 % CI: 0.50, 0.78), indicating long-memory behavior with mean-reversion, similar to CVIX and CIV.

[6] We also computed the skewness for the Euro Stoxx 50, following Engle and Manganelli (2004), and found that CVIX and CIV negatively impacted (with OLS estimates of -0.0002 for both cases) it statistically (at the 10% level), suggesting increased crash risk. This aligns with what Ren et al. (2023) observed for China.

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