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A Note on Cointegrating and Vector Autoregressive Relationships between CO2 allowances spot and futures prices

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Abstract

This article investigates the cointegrating and vector autoregressive relationships in CO2 allowances spot and futures prices, valid for compliance under the EU Emissions Trading Scheme (EU ETS). Our empirical analysis yields to reject a cointegrating relationship between CO2 spot and futures prices, when accounting for the presence of a structural break in February 2009 (possibly due to the delayed impact of the ``credit crunch" crisis). Then, a vector autoregression analysis (complemented by impulse response functions) indicates that futures prices are relevant for price formation in the spot market (while the opposite is not true). Overall, this analysis appears useful to making informed hedging decisions in the banking and finance industries, while allowing regulated utilities to relate futures prices to better forecasts of spot prices.

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1 Introduction

In the current global fight against climate change, the European Union took the lead of environmental policy making by implementing the world's largest emissions trading scheme for CO_2 emissions, which came into operation on January 1, 2005. In 2008, global carbon markets (including transactions from projects mechanisms) were worth more than €89 billion, up more than 80% year-on-year (Reuters). The purpose of this article is to empirically investigate the relationship between European emission allowance (EUA) spot and futures prices using data from BlueNext and the European Climate Exchange (ECX), *i.e.* the most liquid spot and futures carbon exchanges operating under the EU ETS, respectively.

Previous literature has investigated the main properties of CO_2 allowances spot and futures prices. Daskalakis *et al.* (2009) use a jump-diffusion model to approximate the random behavior of CO_2 spot prices, while Benz and Truck (2009) analyze the spot price behavior with a Markov-switching model. Paolella and Taschini (2008) find that a generalized asymmetric t innovation distribution particularly suits the stylized facts of CO_2 emissions spot data. Finally, Lin and Lin (2007) model CO_2 spot prices as a result of mean-reversion with varying trends, combined with state-dependent price jumps and volatility structure. In addition, they show that mean-reversion fares better in forecasting futures prices.

Cointegrating and vector autoregressive relationships between CO_2 spot and futures prices have been addressed by two previous empirical studies. Uhrig-Homburg and Wagner (2007) develop a cost-of-carry approach during 2005-2006 in the EU ETS, and find evidence of a cointegrating relationship. Their results suggest that the carbon futures market was already well functioning at the time, and that the no-arbitrage relationship seems to hold, although market inefficiencies still existed temporarily. Due to banking restrictions implemented between 2007 and 2008 (Alberola and Chevallier (2009)), the weak form of informational efficiency in the European CO_2 market is violated during the whole Phase I (2005-2007). Other authors have shown that the cost-of-carry relationship does not hold between spot and futures prices (Daskalakis and Markellos (2008), Milunovich and Joyeux (2007)). Benz and Hengelbrock (2008) further investigate this question. They conduct a vector error correction model in the ECX futures and Nord Pool spot markets by making use of high frequency data. Their results indicate that the time series from Nord Pool and ECX are cointegrated. Intraday transaction prices also allow them to use detailed insights into trading patterns, and to investigate efficiency measures. Finally, Borak et al. (2006) investigate the modelling of the convenience yield in the European carbon market. They show that the market has changed from initial backwardation to contango with significant convenience yields in futures contracts for the Kyoto commitment period starting in 2008. Their main result features that a high fraction of the yields can be explained by the price level and volatility of the spot prices.

In this article, the econometric analysis consists in a cointegration and vector autoregressive analysis to investigate the relationships between CO_2 allowances spot (BlueNext) and futures (ECX) prices. The central result is that futures prices lead the price discovery process in the EU ETS markets. This study differentiates from Uhrig-Homburg and Wagner (2007) and Benz and Hengelbrock (2008) by *(i)* testing explicitly for the existence of cointegrating relationship between CO_2 spot and futures prices during Phase II, and *(ii)* developing additional statistical tests such as: detecting structural breaks in the time-series used, conducting impulse-response analysis and structural instability tests. Compared to Milunovich and Joyeux (2007), who also investigated the price discovery in the EU ETS markets, this article brings updated results with respect to Phase II price developments. Overall, these results bring a more complete picture of the contemporary relationships between spot and futures prices in the EU ETS.

The findings in this paper are threefold: *1)* the presence of one cointegrating relationship between CO_2 spot and futures prices is subject to the inclusion of a structural break in the data, as highlighted by the Zivot and Andrews (1992) test; *2)* vector autoregression analysis (VAR, Sims (1980)) indicates that futures prices are relevant for spot price formation, while the opposite is not true; and *3)* impulse response functions analysis (Pesaran and Shin (1998)) and Ordinary Least Squares-Cumulative Sum of Squares (OLS-CUSUM, Kramer and Ploberger (1992)) tests allow to better identify the sensitivity of CO_2 prices to shocks in a context of structural instability, possibly due to a delayed adjustment of the EU ETS to the "credit crunch" crisis. These findings indicate that reliable price signals in the EU ETS may be found by looking at the futures market. These economic and financial implications are also motivated by the relatively higher liquidity of the ECX CO_2 futures market compared to the BlueNext CO_2 spot market.

The remainder of the article is organized as follows. Section 2 recalls some theory on the relationships between spot and futures prices for commodity markets. Section 3 applies unit root tests to the time series of CO_2 spot and futures prices. Section 4 conducts the formal cointegration analysis. Section 5 proceeds with the identification of a well-specified VAR model to the time-series of CO_2 spot and futures prices in levels. Section 6 concludes.

2 Some Theory on the Spot-Futures Relationships on Commodity Markets

Assuming rational expectations and risk-neutral market agents, future spot prices should only deviate from futures prices in case of unexpected shocks. Under such restrictive assumptions, spot prices in the delivery period S_T should equal futures prices $F_{t,T}$ plus a white noise error term ϵ_t with zero mean (Working (1949), Brennan (1958)):

$$S_T = F_{t,T} + \epsilon_t \tag{1}$$

In order to test eq(1), we could run a regression where the observed spot price is regressed against a constant and the traded futures price. If the futures price is an unbiased predictor of the future spot price, then the regression coefficients of the constant term and the futures prices should not be statistically different from, respectively, zero and one. However, we do not perform this regression at this stage since we need to apply first unit root tests to the time-series under consideration. Indeed, if the time-series are not stationary, then testing eq(1) will yield to fallacious regressions.

3 Unit Root Tests

We conduct unit root tests by applying the Augmented Dickey-Fuller (henceforth ADF, Dickey and Fuller (1981)) test regressions to the log-returns of CO_2 spot and futures price series. The daily spot price series is the BlueNext CO_2 spot price from February 26, 2008 to April 15, 2009. The daily futures price series used is composed of the ECX December 2008 futures price from February 26, 2008 to December 15, 2008 (*i.e.*, on the expiration day of the futures contract), and then of the ECX December 2009 futures price from December 16, 2008 to April 15, 2009. As shown by Carchano and Pardo (2009), this choice of rolling over futures contracts will not introduce significant bias in our estimates (see Jagannathan (1985), Brennan and Crew (2000), Miffre and Rallis (2007) for more details on commodity markets). Thus, we follow this approach because of its simplicity. Descriptive statistics for all time-series are given in Table 1. The graphs of all price series may be found in Figure 1.

Moreover, we apply the Zivot and Andrews (1992) unit root test with endogenous structural break detection. Test statistics in Table 2 show that the hypothesis of a unit root is rejected when CO_2 spot and futures prices are taken in logarithmic first-difference transformation[1]. It can be concluded that all time series are integrated of order one (*I(1)*). These results are in line with Daskalakis *et al.* (2009).

4 Cointegration Analysis

To avoid *(i)* running spurious regressions of equation (1) on non-stationary raw time series, and *(ii)* losing important long-run information by taking log first-differenced price series, we first investigate the presence of a cointegration relationship between the CO_2 spot and futures price series. Following the Johansen procedure (Johansen (1992)), the cointegration specification is fitted to the natural logarithms of the spot and futures price series[2].

Table 3 shows the results of the Johansen maximum eigenvalue and trace statistics, as well as the cointegration vector and the model weights. Both tests indicate a cointegration space of $r = 1$, given a 5% significance level. Indeed, the null hypothesis of one cointegrating vector between CO_2 spot and futures prices cannot be rejected at the 5% significance level. Therefore, we specify a vector error correction (VEC) model to take this cointegration restriction into account:

$$\Delta y_T = A_0 + A_1 Ect_{T-1} + A_2 \Delta y_{T-1} + \epsilon_t \tag{2}$$

where $\Delta y_T = \begin{bmatrix} \Delta S_T \\ \Delta F_{T-1,T} \end{bmatrix}$ is a vector of first differences of spot and forward prices, $A_0 = \begin{bmatrix} b_{10} \\ b_{20} \end{bmatrix}$ is a vector of constants, $A_1 = \begin{bmatrix} b_{11} \\ b_{21} \end{bmatrix}$ is a vector measuring the speed of the adjustment to the long-run relationship, and $A_2 = \begin{bmatrix} \gamma_{1,1} & \gamma_{1,2} \\ \gamma_{2,1} & \gamma_{2,2} \end{bmatrix}$ is a coefficient matrix. *Ect* denotes the error correction term.

[1]This transformation is useful to smooth size effects between variables and to ensure the stationarity of the time series under consideration, while being particularly useful in economics since it can be interpreted as the growth rate of the dependent variable.

[2]This modelling choice is common practice for cointegration analysis (see for instance Holden and Perman (1994)).

Table 3 shows the result of the VEC model. The error correction coefficient estimates indicate a slow adjustment of short-term deviations to the long-term relationship. Besides, the error correction model explains both spot and futures prices by their own lagged values. It is interesting to see that in the long-run futures prices move together with spot prices according to the cointegration relationship estimated by a relatively short and simple dynamic repercussion (one day lag).

As shown in Figure 2, the Zivot and Andrews (1992) endogenous structural break test indicates an estimated break point on February 12, 2009 for both CO_2 spot and futures price series, thereby capturing with a lag the likely effect of the "credit crunch" financial crisis.

If we allow for a structural break in the data (Lutkepohl et al. (2004)), we reject the hypothesis of one cointegrating relationship at the 5% significance level, as shown in Table 4. Therefore, a vector autoregression (VAR) appears more suitable to describe the data-generating process.

5 Vector Autoregression Analysis

Next, we estimate a VAR model. A VAR representation is only valid if the respective time series can be considered stationary. Hence, we estimate a VAR:

$$\Delta y_T = A_0 + A_1 \Delta y_{T-1} + A_2 \Delta y_{T-2} + \ldots + A_p \Delta y_{T-p} + \epsilon_t \tag{3}$$

where $\Delta y_T = \begin{bmatrix} \Delta S_T \\ \Delta F_{T-1,T} \end{bmatrix}$ is a vector of spot and futures logreturns, $A_0 = \begin{bmatrix} b_{10} \\ b_{20} \end{bmatrix}$ is a vector of constants, and $A_1 = \begin{bmatrix} \gamma_{1,1} & \gamma_{1,2} \\ \gamma_{2,1} & \gamma_{2,2} \end{bmatrix}$, etc. are the coefficient matrices.

Those results are reported in Table 5. The order of the VAR is chosen by minimizing the value of usual information criteria (Hamilton (1996)). The $AIC(n)$ and $FPE(n)$ criteria indicate to choose a lag order $p = 4$, while the $HQ(n)$ and $SC(n)$ criteria recommend a lag order $p = 3$. For both lag orders, VAR estimates satisfy the required residuals properties in terms of autocorrelation, as indicated by the Portmanteau test. Thus, we choose to adopt the most parsimonious specification of a VAR(3)[3].

Table 6 shows the result of the VAR(3) model. The results are striking. Spot prices

[3]Due to space constraints, the results from the VAR(4) model are not shown here. They may be obtained upon request to the author.

can be explained well by their own lagged prices and futures lagged prices up to order one (Table 6, columns (1) to (6)), while futures prices cannot be explained either by their own lagged values or by lagged values of spot prices (Table 6, columns (7) to (12)). Futures prices in the trading period are relevant for price formation of spot prices, whereas the opposite is not true. This is confirmed by Granger non-causality test (Granger (1969) results given in Table 6. The null hypothesis that spot prices do not Granger cause futures prices cannot be rejected at the 5% level (p-value of 0.08783), while the null hypothesis that futures prices do not Granger cause spot prices must be rejected (p-value of 0.4439). Therefore, according to the definition of Granger causality, lagged values of futures prices can be used for forecasting spot prices. Hence, there is strong evidence that the predictive power of the spot price is weak. Alternatively, the null hypothesis of no instantaneous causality between spot and futures prices cannot be rejected for both tests (p-value of 0.0001) at the usual 5% confidence level. Additional impulse-response analysis and structural stability tests based on OLS-CUSUM tests are given in Figures 3 and 4, respectively.

In Figure 3, the standard deviation of the impulse for CO_2 spot and futures prices may be interpreted as a traditional impulse response function (Pesaran and Shin (1998)) for a particular type of shock affecting either price series. According to previous literature (Mansanet-Bataller et al. (2007), Alberola *et al.* (2008), Hintermann (2010)), such shocks may come primarily from other energy markets and weather conditions. The results from the impulse response functions are: *1)* The response of futures prices to the shock exhibits some magnification between horizons 0 and 8, and the response at horizon 20 is smaller than the initial shock (this is known as the typical hump shape) but may take on negative values; *2)* The response of spot prices at horizon 10 is bounded well above zero. However, the initial response to the shock shows substantial magnification, again producing the hump shape typical of many economic time-series. Thus, we have been able to comment in detail *(i)* the level of the shock on either of the two time-series, *(ii)* the sign of the shock on the impacted time-series, and *(iii)* the temporal pattern for the transmission of the shock through the dynamic structure of the VAR model.

OLS-CUSUM tests (Kramer and Ploberger (1992)) for the presence of structural changes in the components of the VAR(3) model are also shown in Figure 4. OLS-CUSUM tests, which are based on cumulated sums of OLS residuals against a single-shift alternative, confirm the Zivot-Andrews endogenous structural change test: for both spot and futures, we notice structural instability around February 2009. In this context, statistical tests on such CO_2 spot and futures time-series should allow for a structural break in the data. This methodology has been properly conducted in Section 4 for the cointegration analysis based on Lutkepohl et al. (2004) test procedure robust to the presence of structural breaks.

These results extend Uhrig-Homburg and Wagner (2007), and more recently Benz and Hengelbrock (2008), by detailing the modeling of the VAR model used for CO_2 spot and futures allowances, as well as by conducting explicitly an impulse-response analysis. Last but not least, compared to previous literature, our results present updated empirical estimates concerning the relationships between CO_2 spot and futures prices during Phase II.

6 Conclusion

To sum up, the analysis of the relationships between CO_2 spot and futures prices allowed us to derive the following insights: *(i)* there exists a cointegrating relationship between CO_2 spot and futures prices; *(ii)* a vector error correction model explains both spot and futures prices by their own lagged value; *(iii)* if we allow for a structural break in the time-series, such as the delayed impact of the "credit crunch" crisis on CO_2 allowance prices of all maturities in February 2009, we cannot further identify the cointegrating relationship; *(iv)* a vector autoregression model then shows that futures prices are relevant for price formation in the spot market, whereas the opposite is not true; and *(v)* through impulse response functions analysis and OLS-CUSUM tests we further identify responses of CO_2 spot and futures prices to shocks in a context of structural instability.

The central result is that futures prices lead the price discovery process in the EU ETS markets. Reliable price signals in the EU ETS may thus be found by looking at the futures market, which was also true during Phase I of the scheme (Alberola et al. (2008), Hintermann (2010)). These economic and financial implications are also explained by the relatively higher liquidity of the ECX CO_2 futures market compared to the BlueNext CO_2 spot market.

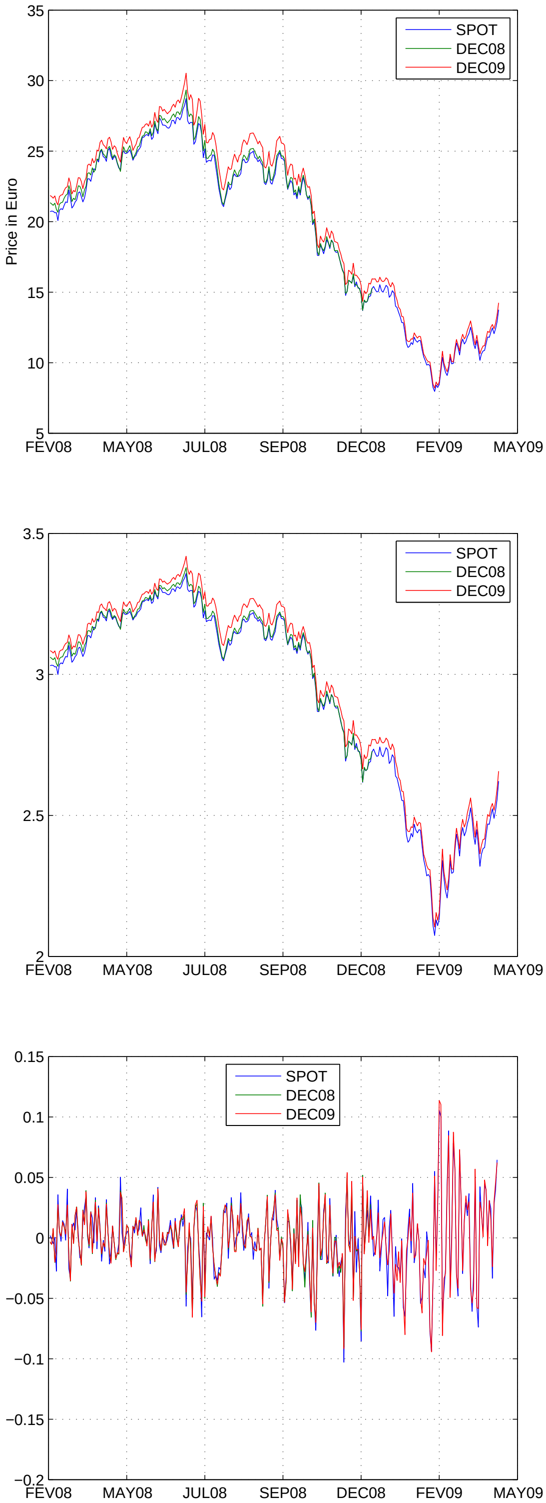
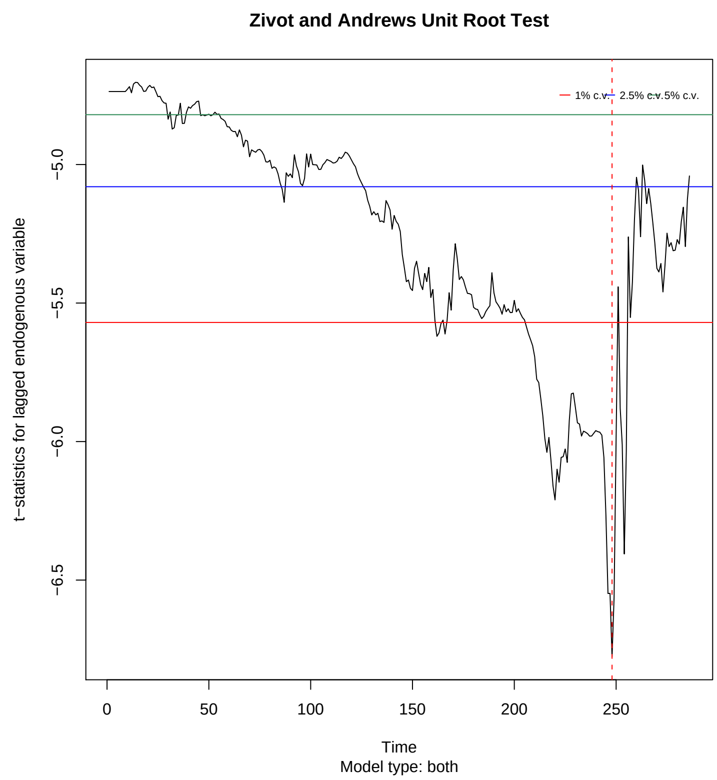


Figure 1
CO_2 Spot and Futures Prices from February 26, 2008 to April 15, 2009: Raw Price Series (top panel), Natural Logarithms (middle panel), and Logreturns (bottom panel)
Source: BlueNext, European Climate Exchange



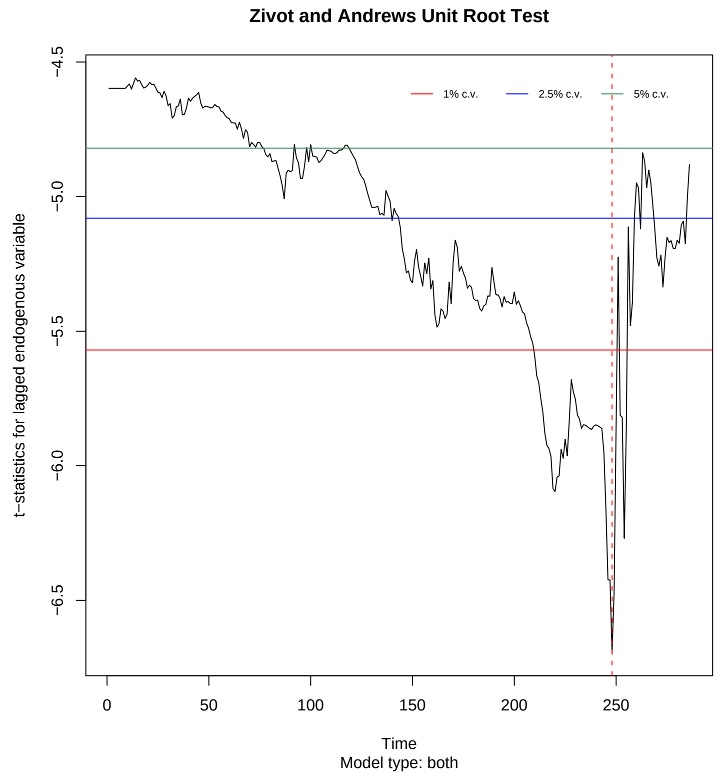


Figure 2
Zivot-Andrews (1992) Test Statistic for CO_2 Allowances Spot (top panel) and Futures (bottom panel) Prices from February 26, 2008 to April 15, 2009

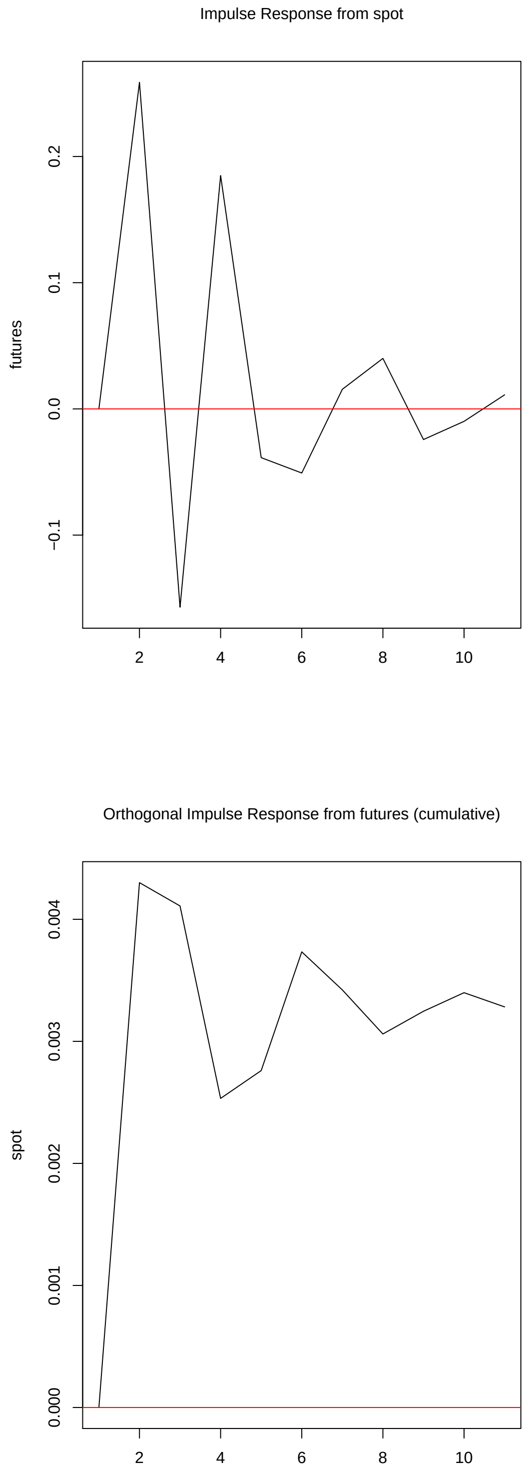


Figure 3
Impulse Responses from CO_2 Allowances Spot to Futures Prices (top panel) and from Futures to Spot Prices (bottom panel) with the VAR(3) Model

Note: In each panel, the horizontal axis reflects the time-horizon, and the vertical axis the standard deviation of the impulse for CO_2 spot and futures prices.

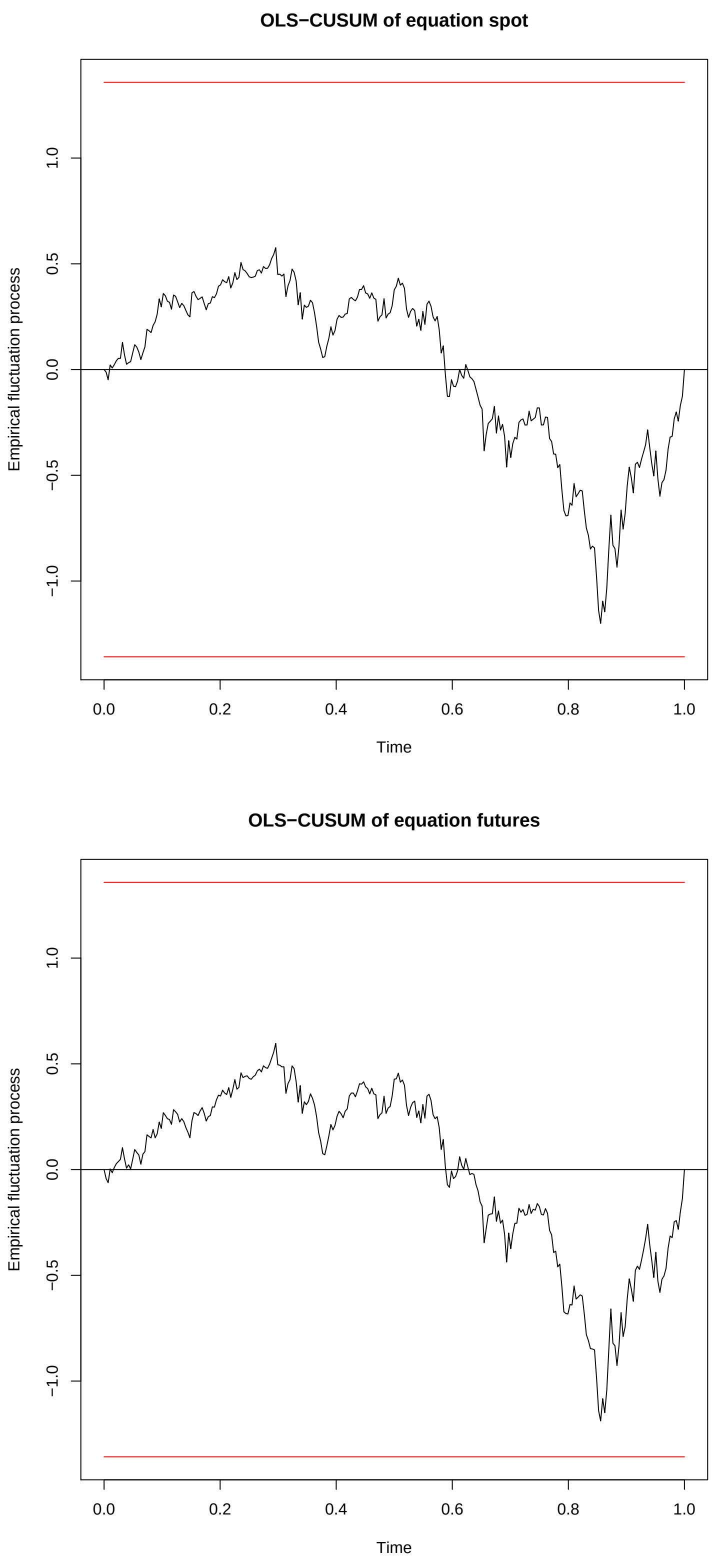


Figure 4
OLS-CUSUM Test for CO_2 Allowances Spot (top panel) and Futures Prices (bottom panel) with the VAR(3) Model

Variable	Mean	Median	Max	Min	Std. Dev.	Skew.	Kurt.	N
Raw Price Series								
Spot	19.61	21.69	28.73	7.96	5.82	-0.43	1.77	288
$DEC08$	22.91	23.59	29.33	13.72	3.55	-0.83	3.03	207
$DEC09$	20.45	22.69	30.53	8.20	6.14	-0.44	1.78	288
Natural Logarithms								
Spot	2.92	3.08	3.36	2.07	0.34	-0.74	2.21	288
$DEC08$	3.12	3.16	3.38	2.62	0.17	-1.16	3.65	207
$DEC09$	2.96	3.12	3.42	2.10	0.35	-0.76	2.23	288
Logreturns								
Spot	-0.01	-0.01	0.11	-0.10	0.03	-0.09	4.22	288
$DEC08$	-0.01	-0.01	0.05	-0.09	0.02	-0.64	4.02	207
$DEC09$	-0.01	-0.01	0.11	-0.09	0.03	0.08	4.59	288

Table 1
Summary Statistics for CO_2 Allowances Spot and Futures Prices

Source: BlueNext, European Climate Exchange

Note: *Spot* refers to BlueNext CO_2 Spot prices, $DEC08$ and $DEC09$ refer to ECX December 2008 and 2009 CO_2 Futures Contracts. *Std.Dev.* stands for Standard Deviation, *Skew.* for Skewness, *Kurt.* for Kurtosis, and N for the number of observations.

Variable	Deterministic Terms	Lags	Test Value	Critical Values		
				1%	5%	10%
$\Delta Spot$	constant	1	-13.2176	-3.44	-2.87	-2.57
$\Delta Futures$	constant	1	-12.9003	-3.44	-2.87	-2.57

ADF Test for CO_2 Spot and Futures Prices

Variable	Estimate (1)	Std. Error (2)	t-value (3)	$Pr(>\mid t \mid)$ (4)
Lagged levels				
(Intercept)	0.009964**	0.004192	2.377	0.018157
$Spot(1)$	-0.3178	0.1945	-1.634	0.103391
Trend	-0.0001164***	0.00003147	-3.699	0.000263
$\Delta Spot(1)$	0.4353**	0.1780	2.445	0.015131
$\Delta Spot(2)$	0.1720	0.1618	1.063	0.288559
$\Delta Spot(3)$	0.2098	0.1452	1.445	0.149718
$\Delta Spot(4)$	0.2574**	0.1319	1.951	0.052082
DU	0.03907***	0.01096	3.565	0.000432
DT	-0.0001269**	0.0004136	-0.307	0.759321
Residuals Std.Error	0.02868			
R-Squared	0.1773			
Adjusted R-Squared	0.1400			
F-Statistic	0.00001			
Test Statistic	-6.7768	-5.57	-5.08	-4.82
Break Point	248			

Zivot-Andrews Test Regression for CO_2 Spot Prices

Variable	Estimate (1)	Std. Error (2)	t-value (3)	$Pr(>\mid t \mid)$ (4)
Lagged levels				
(Intercept)	0.009724**	0.004158	2.338	0.020105
$Futures(1)$	-0.2903	0.1927	-1.506	0.133229
Trend	-0.0001156***	0.00003131	-3.693	0.000269
$\Delta Futures(1)$	0.4273**	0.1763	2.424	0.016024
$\Delta Futures(2)$	0.1750	0.1605	1.090	0.276603
$\Delta Futures(3)$	0.1986	0.1438	1.381	0.168426
$\Delta Futures(4)$	0.2477**	0.1300	1.906	0.057764
DU	0.03953***	0.01090	3.627	0.000343
DT	-0.0001371**	0.0004108	-0.334	0.738822
Residuals Std.Error	0.0285			
R-Squared	0.1775			
Adjusted R-Squared	0.1403			
F-Statistic	0.00001			
Test Statistic	-6.6947	-5.57	-5.08	-4.82
Break Point	248			

Zivot-Andrews Test Regression for CO_2 Futures Prices

Table 2
Augmented Dickey-Fuller (Dickey and Fuller (1981)) and Zivot-Andrews (1992) Unit Root Tests for CO_2 Spot and Futures Prices

Note: *Spot* refers to BlueNext CO_2 spot prices, and *Futures* to ECX December 2008/2009 CO_2 futures prices, transformed in log-returns. Critical values are provided in Dickey-Fuller (1981) and Zivot-Andrews (1992). The Zivot-Andrews model is estimated with both intercept and trend for a maximal lag of order 4. *** denotes 1%, ** 5%, and * 1% significance levels. The Zivot-Andrews Test Statistic is provided with 1%, 5%, and 10% significance levels in columns (2), (3), and (4) respectively. All tests are based on heteroskedasticity consistent standard errors. The number of observations is 289.

Hypothesis	Statistic	10%	5%	1%
$r \leq 1$	0.49	6.50	8.18	11.65
r=0	19.73	12.91	14.90	19.19

Cointegration Rank: Maximum Eigenvalue Statistic

Hypothesis	Statistic	10%	5%	1%
$r \leq 1$	0.49	6.50	8.18	11.65
r=0	20.22	15.66	17.95	23.52

Cointegration Rank: Trace Statistic

Variable	$Spot(1)$	$Futures(1)$
$Spot(1)$	1.0000	1.0000
$Futures(1)$	-1.022703	-0.7516003

Cointegration Vector

Variable	$Spot(1)$	$Futures(1)$
$\Delta Spot$	0.02466715	-0.01388427
$\Delta Futures$	0.20443046	-0.01331373

Model Weights

Variable	$\Delta Spot$	$\Delta Futures$
Error Correction Term		
ect	-0.0246672	-0.2044305
Deterministic		
constant	0.0008731	0.0158048
Lagged differences		
$\Delta Spot(1)$	-0.1887184	0.3311120
$\Delta Futures(1)$	0.3575622	-0.1463355

VECM with $r = 1$

Table 3
Cointegration Analysis of CO_2 Spot-Futures: Johansen Maximum Eigenvalue, Trace Statistics, Cointegration Vector, Model Weights, and Vector Error Correction Model (VECM)

Note: *Spot* refers to BlueNext CO_2 spot prices, and *Futures* to ECX December 2008/2009 CO_2 futures prices, transformed to natural logarithms. Lag order in parenthesis. r is the cointegration rank. *ect* refers to the Error Correction Term. The number of observations is 289.

Hypothesis	Statistic	10%	5%	1%
$r \leq 1$	6.88	5.42	6.79	10.04
r=0	48.96	13.78	15.83	19.85

VECM with Structural Break: Cointegration Rank Trace Statistic

Variable	$Spot(1)$	$Futures(1)$
$Spot(1)$	1.0000	1.0000
$Futures(1)$	-0.9843966	-1.780992

VECM with Structural Break: Cointegration Vector

Variable	$Spot(1)$	$Futures(1)$
$\Delta Spot$	-0.47893305	0.05267858
$\Delta Futures$	-0.03596668	0.05306730

VECM with Structural Break: Model Weights

Table 4
VECM with Structural Break: Cointegration Rank Trace Statistic, Cointegration Vector and Model Weights

Note: *Spot* refers to BlueNext CO_2 spot prices, and $Futures$ to ECX December 2008/2009 CO_2 futures prices, transformed to natural logarithms. Critical values are provided in Lutkepohl et al. (2004). Lag order in parenthesis. r is the cointegration rank. *ect* refers to the Error Correction Term. The number of observations is 289.

Lag	1	2	3	4	5	6	7	8
$AIC(n)$	-1.695238	-1.710303	-1.715954	-1.716008	-1.714676	-1.712785	-1.713793	-1.712551
$HQ(n)$	-1.691061	-1.704038	-1.707600	-1.705566	-1.702146	-1.698166	-1.697086	-1.693756
$SC(n)$	-1.684826	-1.694685	-1.695130	-1.689978	-1.683440	-1.676343	-1.672145	-1.665697
$FPE(n)$	0.000434	0.000373	0.000353	0.000353	0.000358	0.000364	0.000361	0.000365

Diagnostic Tests						
Lag	$Q_1$6	p value	JB_4	p value	$MARCH_5$	p value
$p = 3$	57.4637	0.2800	38.6343	0.00001	94.0891	0.00003

Table 5
VAR Optimal Lag Length Determination for CO_2 Spot and Futures Prices

Note: *Spot* refers to BlueNext CO_2 spot prices, and *Futures* to ECX December 2008/2009 CO_2 futures prices, transformed to logreturns. $AIC(n)$ refers to the Akaike Information Criterion for a lag of order n, $HQ(n)$ refers to the Hannan-Quinn Criterion for a lag of order n, $SC(n)$ refers to the Schwarz Criterion for a lag of order n, and $FPE(n)$ refers to the Final Prediction Criterion for a lag of order n. The number of observations is 289. Diagnostic tests are provided for the optimal lag length $p = 3$. Q_{16} refers to the Ljung-Box-Pierce Portmanteau Test Q Statistic with a maximal lag of order 16, JB_4 is the Jarque-Berra Normality Tests Statistic for a maximal lag of order 4, and $MARCH_5$ is the Multivariate ARCH Test Statistic for a maximal lag of order 5.

Parameter	$Spot(1)$ (1)	$Futures(1)$ (2)	$Spot(2)$ (3)	$Futures(2)$ (4)	$Spot(3)$ (5)	$Futures(3)$ (6)	$Spot(1)$ (7)	$Futures(1)$ (8)	$Spot(2)$ (9)	$Futures(2)$ (10)	$Spot(3)$ (11)	$Futures(3)$ (12)
Estimate	-0.4627*	0.6935**	-0.5379*	0.2998	0.008649	0.1169	0.2587	-0.01406	-0.03377	-0.1914	0.2539	-0.1132
Standard Error	0.2767	0.2765	0.3119	0.3130	0.2768	0.2753	0.2763	0.2761	0.3115	0.3125	0.2764	0.2749

Diagnostic Tests	*Spot*	*Futures*
$R-Squ.$	0.1017	0.09056
$Adj.R-Squ.$	0.0789	0.0675
SE	0.02949	0.02945
$Log-Lik.$	1646.433	1646.433
$F-Stat.$	0.0001	0.0004

Granger Causality Test	Statistic	p-value
Cause=Futures		
Granger	0.8941	0.4439
Instant	138.7813	0.0001
Cause=Spot		
Granger	2.1933	0.08783
Instant	138.7813	0.0001

Table 6

VAR(3) Estimation Results for CO_2 Spot and Futures Prices

Note: *Spot* refers to BlueNext CO_2 spot prices, and *Futures* to ECX December 2008/2009 CO_2 futures price, transformed to logreturns. The optimal lag order for the VAR is $p = 3$. Columns (1) to (6) contains the parameter estimates and corresponding standard errors for the *Spot* equation, while columns (7) to (12) contain the results of the *Futures* equation. Lag order in parenthesis. *** denotes 1% significance, ** 5% significance, and * 10% significance levels. All tests are based on heteroskedasticity consistent standard errors. The number of observations is 289. $R-Squ.$ stands for the R-Squared, $Adj.R-Squ.$ for the Adjusted R-Squared, SE for the standard error, $Log-Lik.$ for the log-likelihood, and $F-Stat.$ for the F-Statistic. The value of the $F-Stat.$ is the p-value. The *Granger* Causality Test Statistic provided is the $F-Test.$ *Instant* denotes instantaneous causality between variables. The value of the instantaneous Granger Causality Test provided is the χ^2-statistic.

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