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TRANSACTION COSTS AND NONLINEAR MEAN REVERSION IN THE EU EMISSION TRADING SCHEME*

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Abstract

The potential benefits of tradable pollution permits and allowances can be limited by transaction costs. The implementation and operation of the European Union Emission Trading Scheme (EU ETS) involves transaction costs such as internal costs, capital costs, and consultancy and trading costs. This paper investigates the effect of transaction costs on market efficiency and price discovery in the EU ETS. An empirical assessment of nonlinear mean reversion is provided using threshold cointegration, which allows for asymmetric regime-dependent adjustment to the equilibrium relationship between European Union Emission Allowances (EUA) spot and futures prices. The mean reversion process reveals nonlinear and regime-dependent adjustment, and thus the empirical evidence indicates that transaction costs affect the mean reversion behavior and restrain market efficiency and price discovery.

Keywords: EU ETS, market efficiency, nonlinear mean reversion, price discovery, threshold cointegration, transaction costs
JEL Classification Codes: G15, Q50

I. *Introduction*

The potential benefits of tradable pollution permits and allowances can be impeded by the

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presence of transaction costs. The implementation and operation of the European Union Emission Trading Scheme (EU ETS) involves transaction costs such as internal costs, capital costs, and consultancy and trading costs. This paper investigates the effect of transaction costs on market efficiency and price discovery in the EU ETS. An empirical assessment of market efficiency is provided using the threshold vector error correction model (VECM), which allows for nonlinear regime-dependent adjustment to the equilibrium relationship between EUA carbon spot and futures prices.

The EU ETS was introduced in January 2005. Since then, the EU ETS has been regarded as the key instrument of the European Commission's climate change program to reduce greenhouse gas emissions. However, as discussed in Stavins (1995), transaction costs can be the main obstacle preventing the trading of permits. Transaction costs reduce trading volume and frequency, and increase abatement costs. The effect of transaction costs on the performance of pollution control markets has been evaluated in many studies, including Tietenberg (1980) and Atkinson and Tietenberg (1991). Although the emission trading market has been growing, transaction costs are significantly large - up to 18% of the allowance price depending on firm size (Jaraitė *et al.*, 2010). Heindl (2012) estimated overall annual transaction costs in the German ETS market to be about 8.7 million euros. About 69% of transaction costs are from the measurement, reporting, and verification of emissions; 19.57% is from trading permits; and 11.43% is from information costs.

Transaction costs may affect the market efficiency and price discovery in the EU ETS. The equilibrium relationship between European Union Emission Allowances (EUA) spot and futures prices can be disturbed by transaction costs, and the deviation from the equilibrium tends to show persistent behavior. Prolonged and persistent deviations also affect market efficiency by causing the incorrect matching of spot prices to futures prices. This paper investigates the effects of transaction costs on market efficiency in the EU ETS. As the threshold VECM explains nonlinear adjustment to an equilibrium relationship, we employ the regime-dependent threshold VECM to assess the nonlinear dynamic adjustment of carbon prices.

The EU ETS is the mechanism for establishing the fair price of carbon dioxide emission allowances. As the price of emission is determined by market players, developed and developing countries can pay and receive fair compensation. The total emission cap is limited, so there is a price that reaches the emission reduction goal. Given market efficiency, the price provided by the market to the market players can give them the appropriate information to evaluate their emission allowances. By analyzing market efficiency, we can determine the degree to which the carbon trading scheme can generate the proper allocation and fair price of emission allowances.

For the pilot trading period, Phase I (2005-2007), EUA prices dropped significantly following news of large allocations of allowances. Furthermore, non-bankability and grandfathering caused carbon prices to approach zero in 2007 as the pilot trading period ended. As the market moved to Phase II of the Kyoto commitment period (2008-2012), the EU ETS market was less affected by sharp drops in carbon prices and the trading volume had increased significantly.

Empirical analysis finds a cointegrating relationship between EUA carbon spot and futures prices during Phase II of the Kyoto commitment period. However, the VECM estimation results show that futures prices do not react to deviations from the equilibrium relationship. In fact, the threshold VECM estimation results indicate that the mean reversion process exhibits nonlinear regime-dependent adjustment. In Regime 1, where the equilibrium error is smaller than the lower threshold value, the carbon futures price responds strongly to the equilibrium error, and thus mean reversion behavior appears to be taking place. On the other hand, in Regime 2, where the equilibrium error is bounded by lower and upper threshold values, the futures price responds sluggishly and the deviation from the equilibrium relationship takes on a persistent quality. The size and frequency of Regime 2 are large. Thus, empirical evidence indicates that in the EU ETS transaction costs affect market efficiency and price discovery.

Market efficiency in the EU ETS has been analyzed using the equilibrium relationship between carbon emission allowance spot and futures prices. Joyeux and Milunovich (2010) investigated the extent of market efficiency during the pilot period from June 2005 to December 2007. Although the cointegration analysis fails to support market efficiency, recursive cointegration estimates approach theoretical values when applied to a more recent subsample period. Trück *et al.* (2012) find wide and pronounced deviations from the equilibrium relationship in the EU ETS over both the pilot period from 2005 to 2007 and the Kyoto commitment period from 2008 to 2012.

In many studies of the EU ETS market, the price discovery process has been evaluated using the equilibrium relationship between carbon spot and futures prices. Uhrig-Homburg and Wagner (2009) find that the futures price leads the price discovery process during Phase I. These results are supported by Rittler (2012) who has shown that the futures market leads the spot market. On the other hand, Joyeux and Milunovich (2010) find that during Phase I spot and futures prices both share information and jointly contribute to price discovery. In these studies, the price discovery behavior and market efficiency of the EU ETS have been evaluated by using the linear VECM. However, the linear VECM does not allow for the prevalent effect of transaction costs, which disturbs the mean reversion process of carbon prices. In this paper, we allow for the effect of transaction costs with the aim of explaining the stylized characteristics of nonlinear mean reversion behavior. Using the threshold VECM, we provide an assessment of regime-dependent nonlinear price discovery and market efficiency in the EU ETS.

Daskalakis *et al.* (2009) investigated the development of the EU ETS market focusing on the prohibition and allowance of bankability in Phase I and Phase II, respectively. Related studies focus on the market drivers in the EU ETS, including Alberola *et al.* (2008), Fezzi and Bunn (2009), Bredin and Muckley (2011), Creti *et al.* (2012), and Aatola*et al.* (2013). In particular, Alberola *et al.* (2008) analyzed carbon price determination using market drivers such as energy price and temperature.

The paper is organized as follows. The relationship between the futures price and the spot price and econometric methods are provided in section II. The data and descriptive statistics are explained in section III. The main results are provided in section IV. Section V concludes our research.

II. *The Model and Econometric Methods*

The evaluation of market efficiency in the EU ETS carbon market can be based on the spot-futures parity, which is the equilibrium relationship between spot and futures prices. The spot-futures parity condition states that, if arbitrage opportunity can be realized without friction, the futures price should become equal to the cost-carry, the sum of the spot price and carrying costs. At time t, let F_t denote the price of a futures contract and S_t the spot price. If H_t denotes the theoretical futures price, from the spot-futures price parity condition, we have the following relationship:

$$H_t = S_t \ e^{r_t m} \tag{1}$$

where r_t is the risk-free interest rate and m is the time to the maturity.

Carrying costs may include the convenience yield and storage costs. The carbon emission certificate does not entail a storage cost. In addition, in the EU ETS the settlement of carbon offsets is conducted once per year, and thus the emission certificate does not engender a convenience yield. The parity condition (1) has been used in the literature, including Uhrig-Homburg and Wagner (2009) and Joyeux and Milunovich (2010).

The price parity condition provides the equilibrium relationship between actual and theoretical carbon prices:

$$f_t = \beta h_t + w_t \tag{2}$$

where f_t and h_t denote actual and theoretical futures prices, respectively, in terms of natural logarithms.

Actual and theoretical futures prices are non-stationary, and thus the parity condition imposes the stationarity of the cointegrating relationship w_t. Therefore, the spot-futures price parity condition supports the cointegrating relationship between actual and theoretical futures prices. In empirical analysis, we evaluate the stationarity of the cointegrating relationship between carbon prices using the Johansen cointegration test.

The mean reversion process of carbon prices to the equilibrium relationship can be assessed using the vector error correction model (VECM).

$$\Delta x_t = \mu + \alpha w_{t-1}(\beta) + \Sigma_{i=1}^{k} \Gamma_i \Delta x_{t-i} + u_t \tag{3}$$

where $x_t = (f_t, h_t)'$, $\mu = (\mu_f, \mu_h)'$, $\alpha = (\alpha_f, \alpha_h)'$, and $w_t(\beta) = f_t - \beta h_t$.

The cointegrating relationship $w_t(\beta)$ is stationary if the price parity condition holds. As a result, the price parity condition implies an equilibrium relationship between the actual and theoretical futures prices.

The adjustment vector α represents the response of carbon prices to the equilibrium relationship. As the long-run equilibrium relationship implies dynamic mean reversion behavior, the price parity condition provides information about future change in carbon prices. For example, if the actual futures price is higher than the theoretical one, the futures price is expected to decline to regain the price parity. Equation (3) has the vector error correction model (VECM) specification, and the price parity can be interpreted as an error correction term in the VECM specification.

Now, we consider the threshold VECM, which has been developed by Hansen and Seo (2002). Threshold cointegration allows for nonlinear adjustment to the equilibrium relationship. The threshold VECM enables us to detect the presence of asymmetric regime-dependent mean reversion behavior. Seo (2003) extends the two-regime threshold VECM to a three-regime model. Our study investigates the effect of transaction costs, and thus the three-regime threshold VECM is considered appropriate for the analysis.

Threshold VECM

$$\Delta x_t = \begin{cases} (\mu_1 + \alpha_1 w_{t-1} + \sum_{j=1}^{k} \Gamma_{1j}\, \Delta x_{t-j}) 1(w_{t-1} \leq \gamma_1) + \\ (\mu_2 + \alpha_2 w_{t-1} + \sum_{j=1}^{k} \Gamma_{2j}\, \Delta x_{t-j}) 1(\gamma_1 < w_{t-1} \leq \gamma_2) + \\ (\mu_3 + \alpha_3 w_{t-1} + \sum_{j=1}^{k} \Gamma_{3j}\, \Delta x_{t-j}) 1(w_{t-1} > \gamma_2) + u_t \end{cases} \tag{4}$$

The threshold VECM (4) posits three regimes, which are determined by the magnitude of the equilibrium error compared to the threshold parameters γ_1 and γ_2. Regime 1 is in effect where the equilibrium error is smaller than γ_1, Regime 2 where the error is between γ_1 and γ_2, and Regime 3 where the error is larger than γ_2.

The arbitrage opportunity cannot be realized if the deviation from the price parity is bounded by transaction costs, since the arbitrage does not produce net gain, and thus the equilibrium error may prevail. However, if the arbitrage opportunity exceeds the transaction costs, the opportunity is likely to be exploited. Thus, the mean reversion process may reveal regime-dependent asymmetric behavior. If a band of non-adjustment exists, then the adjustment coefficient of the corresponding band is likely to be close to zero. Regime 2 can be interpreted as such a band of non-adjustment, and this may explain the effect of transaction costs on the mean reversion behavior of carbon prices in the EU ETS.

The threshold VECM assumes that each regime has regime-specific adjustment coefficients and intercept. Chevallier (2011) applied the threshold VECM to the carbon-macroeconomy relationship between industrial production and carbon prices. In this study, we explore the asymmetric dynamic properties of the mean reversion process to the equilibrium relationship based on the futures-spot carbon price parity.

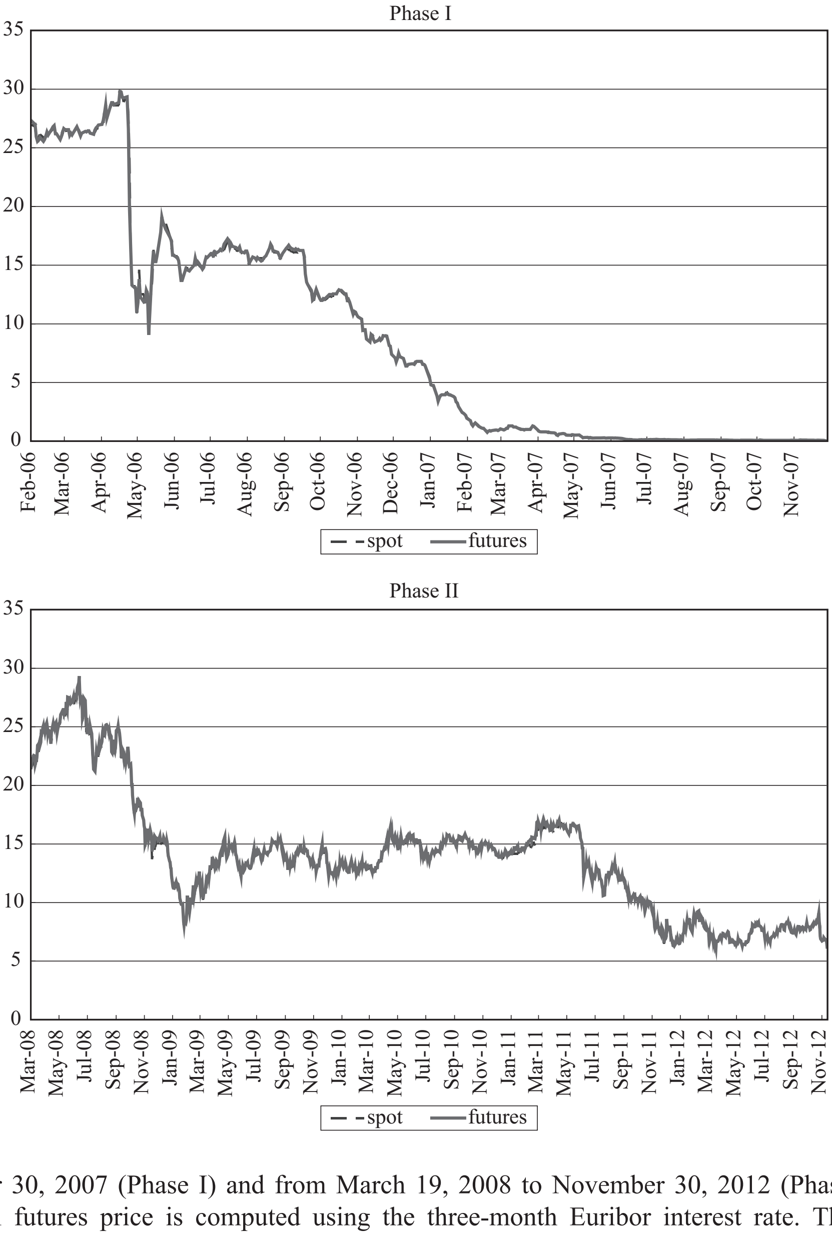
III. *Data*

The EU Emission Trading Scheme (ETS) was launched in 2005 to confront climate change and comply with the Kyoto Protocol. The regulatory coverage of factories, power stations, and other installations regulated by the EU ETS has increased continuously and as of Phase II accounts for almost half of the CO_2 emissions and 40% of the total greenhouse gas emissions in the EU.

The first ETS trading period lasted three years, from January 2005 to December 2007 and the second lasted five years, from January 2008 to December 2012. The third trading period began in January 2013 and will continue until December 2020. Compared to 2005, when the EU ETS was first implemented, the proposed caps for the year 2020 represent a 21% reduction of greenhouse gases. A number of significant changes have occurred in the EU ETS since the first trading period launched in 2005 and the most significant change in Phase II was the bankability of emission allowances to the next period. The price of the emission allowance converged to 0 as the date approached the end of Phase I. Phase III has extended auctioning to a majority of permits, harmonized rules for the remaining allocations, and included other greenhouse gases.

Figure 1 shows the time plots of ETS carbon prices during Phase I and Phase II. The data set is EU ETS allowance spot and near month futures prices, obtained from Bluenext and European Energy Exchange, respectively. We use the daily data from February 3, 2006 to

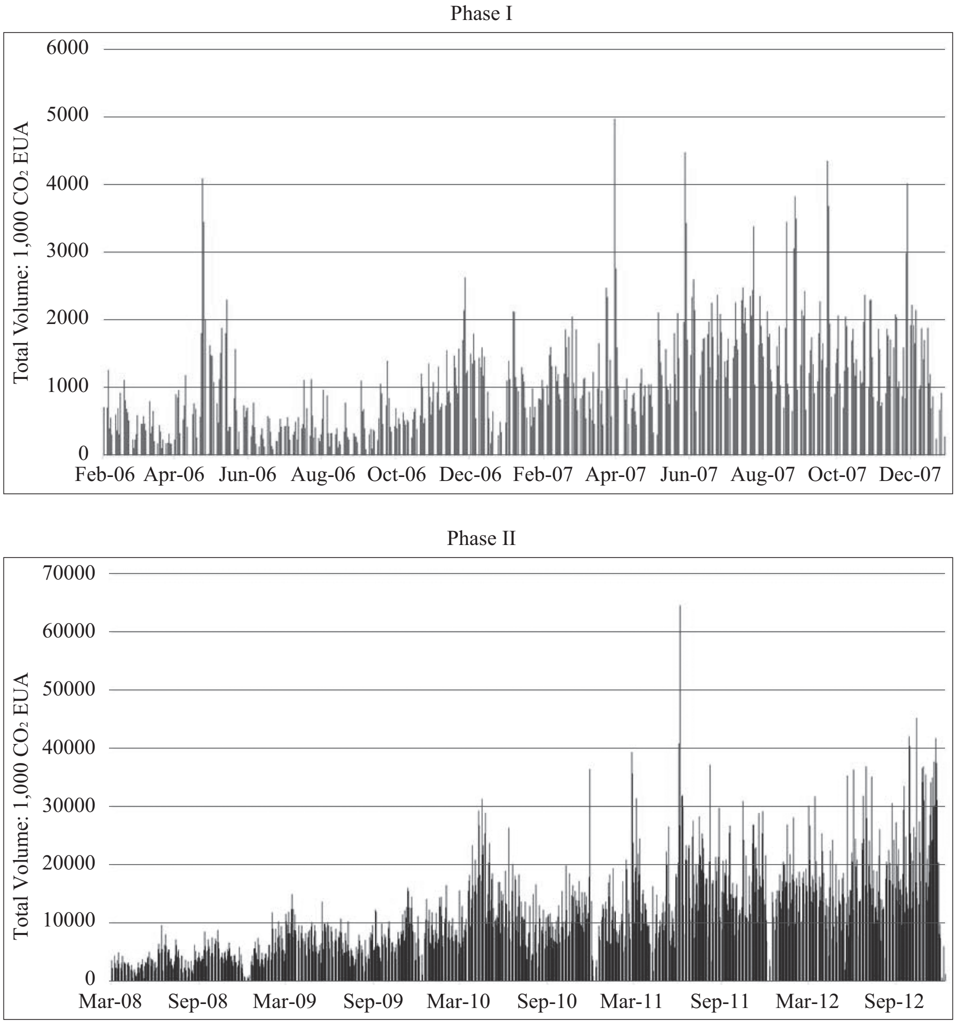
Figure 1. EU ETS Carbon Prices



November 30, 2007 (Phase I) and from March 19, 2008 to November 30, 2012 (Phase II). The theoretical futures price is computed using the three-month Euribor interest rate. The time to maturity of the futures contracts is applied to obtain the theoretical parity price.

Figure 1 shows a sharp drop in carbon prices in April 2006, reflecting the misallocation of allowances to individual firms. This sharp decline was caused by an oversupply of allowances in the experimental stage of Phase I. This might have reflected a moral hazard problem, in that firms may tend to underreport their abatement abilities to obtain more EUAs. Thus the total

FIGURE 2. TRADING VOLUME

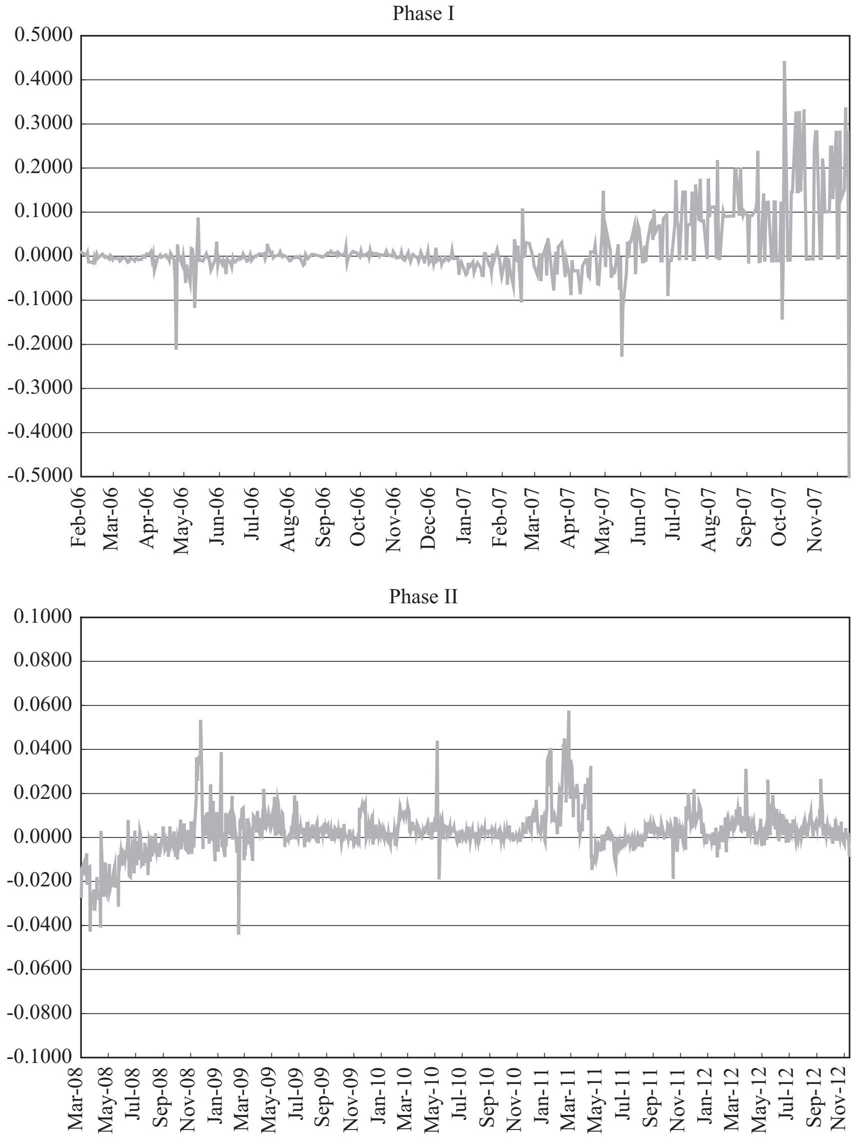


amount of EUAs issued was more than necessary, causing their prices to drop dramatically in Phase I.

Although the prices of EU ETS carbon allowances decreased in 2008, stable carbon price movement can be observed during the Kyoto commitment period. The Global Financial Crisis more or less has affected the demand for emission allowances and caused a large surplus during Phase II.

Figure 2 shows EU ETS trading volumes during Phase I and Phase II. The trading volume data set was obtained from the European Energy Exchange. The increased ETS trading volume in Phase II compared to that in Phase I was caused by the introduction of bankability and the termination of grandfathering. In addition, during Phase II, in spite of the influence of the

FIGURE 3. PRICING ERROR: $e_t = f_t - h_t$



Global Financial Crisis on EU ETS operation, trading volume steadily increased.

The futures price was relatively stable in Phase II after the sharp decline in 2008. The two phases have different principles. Storage or bankability was not allowed during Phase I, but was allowed as of Phase II. Additionally, the initial allocation procedure was different. In Phase I, the allocation was based on grandfathering instead of auctioning. On the other hand, in Phase II, although the allocation still allowed grandfathering, it began to adopt auctioning. As a result, while by the close of 2007, the end of Phase I, the value of the EUA had become almost zero,

TABLE 1. DESCRIPTIVE STATISTICS

	Phase I				Phase II			
	Δs_t	Δf_t	b_t	e_t	Δs_t	Δf_t	b_t	e_t
Mean	-0.0147	-0.0147	0.0163	0.0093	-0.0010	-0.0010	0.0084	0.0039
Median	0.0000	0.0000	0.0041	-0.0021	0.0000	0.0000	0.0053	0.0023
Std. Deviation	0.0915	0.1317	0.1303	0.1307	0.0270	0.0271	0.0143	0.0154
Skewness	-0.3046	-1.8864	-6.3406	-6.3127	0.2589	0.0183	6.1500	5.0064
Kurtosis	9.5014	47.9844	79.0784	78.2948	8.4822	6.8021	62.6916	51.0718
Jarque-Bera	871	41,606	121,454	119,003	1,534	731	187,886	121,964
(P-value)	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0000)
Ljung-Box Q	7.9035	23.7313	52.9328	53.0570	3.7764	2.0782	748.9146	745.6823
(P-value)	(0.0049)	(0.0000)	(0.0000)	(0.0000)	(0.0520)	(0.1494)	(0.0000)	(0.0000)
ARCH-LM	65.6576	130.5876	2.4476	2.5215	37.6276	54.6567	2192.422	2198.462
(P-value)	(0.0000)	(0.0000)	(0.1161)	(0.1129)	(0..0000)	(0.0000)	(0.0000)	(0.0000)

by the close of 2012, the end of Phase II, it was approximately 6.5 euro per metric ton of carbon dioxide.

Figure 3 shows the time plot of the pricing error $e_t = f_t - h_t$ during Phase I and Phase II. The pricing error represents the deviation of the futures price from the theoretical parity price. During the pilot period, wide fluctuations in pricing error are observed and the log-transformed values amplify variations excessively as the carbon prices approach zero. For the Kyoto commitment period, the carbon market has changed from initial backwardation to contango as observed by Trück *et al*. (2012).

Table 1 shows descriptive statistics of the carbon spot and futures price changes, the basis, and the pricing error. The futures price changes, Δf_t, is the series calculated by $f_t - f_{t-1}$. Likewise, the spot price changes, Δs_t, is the series of $s_t - s_{t-1}$. The basis b_t is given by $f_t - s_t$ for the maturity dates of futures contracts in Phase I and Phase II. The series of pricing errors, e_t, are the deviations of actual futures prices from the theoretical parity prices, $f_t - h_t$.

The average growth rate of the EUA spot price is negative, especially during Phase I and a similar pattern is observed for the average futures price growth rate. For the pilot period, the carbon spot and futures prices revealed a decreasing trend. As the carbon prices approach zero, the logged values drop sharply. The average growth rate of carbon prices is negative, and large negative values tend to increase the variance and standard deviation. The changes in carbon prices show skewed and leptokurtic behavior, and thus the normal distribution hypothesis can be rejected. The price changes also display serial correlation and conditional heteroskedasticity.

The standard deviation of the pricing error is larger in Phase I than Phase II. The skewness of pricing error has a negative value in Phase I and a positive value in Phase II. The leptokurtic behavior of the pricing error appears prevalent in both Phase I and Phase II. Thus, the Jarque-Bera test rejects the normality hypothesis. The Q-statistic and ARCH LM tests indicate serial correlation and heteroskedasticity of pricing error, respectively.

IV. *Econometric Results*

The price parity condition implies that actual and theoretical futures prices form a cointegrating relationship. We examine the cointegration between actual and theoretical futures prices during Phase II but not Phase I, where grandfathering and non-bankability led to near-zero carbon prices.

Table 2 shows the results of the Johansen cointegration test. The null hypothesis of no cointegration can be rejected at the 5% level while the null of at most one cointegrating relationship is maintained. The cointegrating relationship is found significant for the Kyoto commitment period, Phase II. The VAR lag length is 1, chosen by the Bayesian information criterion (BIC). The test results do not vary greatly across other VAR lag lengths as Table 2 shows. Thus, we conclude that there is one cointegrating relationship between actual and theoretical futures prices.

Table 2. Cointegration Test

VAR Lag Length	Null Hypothesis	Trace Statistics	P-value
1	H_0: $rank=0$	107.3334	0.0000
	H_0: $rank\leq 1$	2.545102	0.6686
2	H_0: $rank=0$	97.78338	0.0000
	H_0: $rank\leq 1$	2.715103	0.6352
3	H_0: $rank=0$	100.7851	0.0000
	H_0: $rank\leq 1$	2.683801	0.6413
4	H_0: $rank=0$	83.53453	0.0000
	H_0: $rank\leq 1$	0.891677	0.3450
5	H_0: $rank=0$	69.91172	0.0000
	H_0: $rank\leq 1$	2.563479	0.6649
6	H_0: $rank=0$	67.11551	0.0000
	H_0: $rank\leq 1$	2.745184	0.6293

1. Linear VECM

Table 3 shows the estimation results of the VECM. The VAR lag length is chosen to be 1 by the BIC. The cointegrating vector is estimated as close to one, which supports the unbiasedness of the price parity condition. Thus, the actual and theoretical futures prices form an equilibrium relationship, and the futures price tends to be equalized to the cost-carry.

However, the adjustment coefficient of the futures price equation has a positive yet insignificant value. The positive value of the coefficient implies that the linear VECM estimates of the adjustment process indicate a weak or reverse response of the futures price to the cointegrating relationship. As the futures price does not respond to the equilibrium error, the deviation from the long-run relationship may persist. On the other hand, the adjustment coefficient of the theoretical price indicates a significant response to the deviation from the long-run relationship.

TABLE 3. VECM ESTIMATION

	Δf_t		Δh_t
β	1		-0.991756
s.e.(β)			(0.00291)
α	0.019064		0.203634
s.e.(α)	(0.05699)		(0.05666)
μ	-0.0017		-0.0089
s.e.(μ)	(0.0021)		(0.0046)
Log-Likelihood		6731.3692	
Akaike Information Criterion		-16.7596	
Bayesian Information Criterion		-16.7218	

2. Threshold VECM

We consider the threshold VECM which allows for regime-dependent nonlinear adjustment to the long-run equilibrium relationship. The EU ETS has been designed to offer market-based reforms of environmental policy, since this approach to pollution control offers advantages over conventional ones. However, transaction costs, which are significant in the tradable-permit system, may reduce trade volume and increase abatement costs. As emission trading involves transaction costs, the mean reversion process may exhibit regime-dependent asymmetric movement. Thus, we apply the threshold VECM to explain the regime-dependent nonlinear adjustment to the long-run equilibrium relationship.

As discussed in section III, during Phase I, grandfathering and non-bankability led to near-zero carbon prices. Thus, the threshold cointegration between actual and theoretical futures prices is only analyzed during Phase II. We apply the tests for threshold cointegration, based on the VECM specification and provided by Hansen and Seo (2002) and Seo (2003). The test statistics are based on a heteroskedasticity-robust covariance estimator.

As Table 4 shows, the tests for threshold cointegration reject the null hypothesis of no threshold effect in dynamic adjustment. The Sup-LM statistic exceeds the 5% critical value, and its p-value is close to zero at a VAR lag length of 1, the value chosen by the BIC. The null hypothesis of linear adjustment can be rejected in favor of threshold cointegration even at other VAR lag lengths. The p-values are computed using bootstrapping with a bootstrap replication of 1,000.

TABLE 4. TESTS FOR THRESHOLD COINTEGRATION

VAR Lag Length	Sup-LM Statistic	5% Critical Value	P-value
1	40.774	38.396	0.019
2	56.727	48.347	0.002
3	69.777	59.799	0.003
4	84.747	69.569	0.001
5	86.583	79.086	0.007
6	97.586	88.259	0.006

Table 5 provides the estimation results of the threshold VECM. The VAR lag length is 1, the value chosen by the BIC. The grid search method is used in the threshold VECM

TABLE 5. THRESHOLD VECM ESTIMATION

	Regime 1		Regime 2		Regime 3	
	Coefficient	Standard Error	Coefficient	Standard Error	Coefficient	Standard Error
μ_f	0.0215	0.0087	-0.0035	0.0087	-0.0055	0.0054
μ_h	0.0119	0.0073	-0.0122	0.0087	-0.0203	0.0187
α_f	-0.7288	0.3096	0.0411	0.2214	0.0757	0.0616
α_h	-0.4259	0.2620	0.2738	0.2212	0.3564	0.2824
$\gamma_1=0.0330$, $\gamma_2=0.0549$						
$P(w_t \leq \gamma_1)=0.2688$, $P(\gamma_1 < w_t \leq \gamma_2)=0.6686$, $P(w_t > \gamma_2)=0.0627$						
Log-Likelihood				6784.6989		
Akaike Information Criterion				-16.8212		
Bayesian Information Criterion				-16.7160		

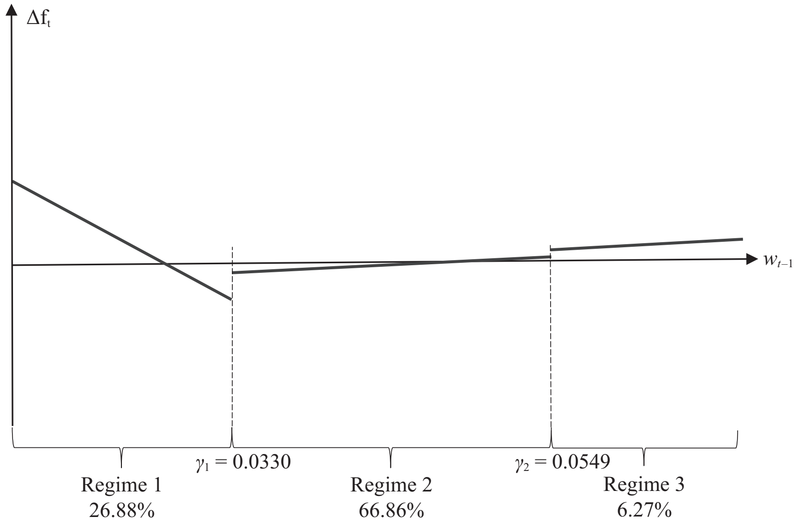
estimation. We take a grid of the threshold values (γ_1, γ_2) from the 5th percentile to the 95th percentile of the equilibrium error. We then search for values of (γ_1, γ_2) that maximize the likelihood function. The estimated coefficients correspond to the values at which the likelihood function is maximized. The Gauss program is used for estimation, and the detailed algorithm can be found in Hansen and Seo (2002).

The estimated threshold values of γ_1 and γ_2 are 0.0330 and 0.0549. Under Regime 1, which corresponds to the period when the futures price is lower than the theoretical parity price by γ_1, the adjustment coefficient of the change in futures price is estimated as -0.7288 with a standard error of 0.3096. As the adjustment coefficient is statistically significant at the 5% size, the futures price responds strongly to the pricing error in Regime 1. In contrast, under Regime 2, which may correspond to the period when the equilibrium error is bounded by the threshold parameters (γ_1, γ_2), the futures price does not respond to the pricing error. The adjustment process does not show mean reversion behavior, and thus the deviation from price parity may persist in Regime 2. Under Regime 3, which corresponds to the period when the futures price exceeds the theoretical parity price by γ_2, the adjustment coefficient of the change in futures price reveals a positive yet statistically insignificant response.

As shown in Table 5, the threshold VECM explains the nonlinear dynamic adjustment of the futures price to the equilibrium relationship between the actual and theoretical futures prices while the linear VECM does not identify the presence of the threshold effect. The log-likelihood of the threshold VECM is significantly higher than that of the linear VECM. Furthermore, the Akaike information criterion indicates that the threshold VECM represents an improvement over the linear VECM, while the Bayesian information criterion increases from -16.7218 to -16.7160.

Figure 4 shows the regime-dependent adjustment process of the futures price. When the equilibrium error belongs to Regime 1, the futures price responds to the equilibrium error to a greater extent. Mean reversion behavior appears strong in the area of Regime 1. The relative frequency of observations in Regime 1 is found to be approximately 26.88%. When the pricing error belongs to Regime 2, the response is small and the slope is flat. The arbitrage opportunity cannot be realized as transaction costs prevent mean reversion and restrain market efficiency and price discovery. Therefore, the mean reversion adjustment process can be restricted by transaction costs, and this indicates the persistence of the deviation from the price parity. The area of Regime 2 occupies about 66.86% of all arbitrage opportunities. When the equilibrium

FIGURE 4. REGIME-DEPENDENT NONLINEAR ADJUSTMENT



error belongs to Regime 3, the response of the change in futures price has a positive sign, but the adjustment coefficient is insignificant. The area of Regime 3 occupies about 6.27% of all arbitrage opportunities. Overall, while the linear VECM indicates a weak and reverse response of the futures price, the threshold VECM estimates reveal regime-dependent nonlinear mean reversion behavior.

These asymmetric adjustment patterns imply that the predictability of the futures price using the price parity condition appears to increase when we allow for nonlinear adjustment. To assess forecasting performance, we obtain out-of-sample forecasts based on the linear and threshold VECMs. The reference model is based on the random walk, which states that future price changes are unpredictable. The linear VECM assumes a linear adjustment to the price parity but we also consider the threshold VECM, which allows for regime-dependent mean reversion. The out-of-sample forecasts for the period January 3, 2011 to November 30, 2012 are obtained by using the recursive forecasting method with an initial estimation period of March 19, 2008 to December 31, 2010. The forecasting horizon is taken as h=1, 5, 10, 15, 20, 30. We examine the root mean squared error (RMSE) and the mean absolute percentage error (MAPE).

As the forecasting horizon increases, the accuracy of out-of-sample forecasts based on the threshold VECM greatly improve, but, for a one-period horizon, accuracy does not improve. In particular, as Table 6 shows, compared to the random walk forecasts, for h=5, threshold VECM forecasts of futures prices show an RMSE improvement of 17% and an MAPE improvement of 15%. The values in the parentheses are the ratios of the RMSE and MAPE values of the VECM models to those of the random walk model reference. The forecasts based on the linear VECM reduce the RMSE by 9% and MAPE by 8%. This suggests that carbon prices reveal nonlinear mean reversion to the price parity, so the analysis of market efficiency and price discovery using the price parity condition had better be based on the threshold rather than linear VECM.

Table 6. Forecasting Accuracy

	h	Random Walk		Linear VECM		Threshold VECM	
RMSE	1	0.0303	(1.00)	0.0306	(1.01)	0.0309	(1.02)
	5	0.0680	(1.00)	0.0620	(0.91)	0.0566	(0.83)
	10	0.0926	(1.00)	0.0866	(0.94)	0.0755	(0.82)
	15	0.1124	(1.00)	0.1072	(0.95)	0.0911	(0.81)
	20	0.1299	(1.00)	0.1248	(0.96)	0.1050	(0.81)
	30	0.1524	(1.00)	0.1496	(0.98)	0.1245	(0.82)
MAPE	1	0.9956	(1.00)	1.0154	(1.02)	1.0169	(1.02)
	5	2.3433	(1.00)	2.1653	(0.92)	1.9864	(0.85)
	10	3.2393	(1.00)	3.0375	(0.94)	2.6923	(0.83)
	15	4.0381	(1.00)	3.8323	(0.95)	3.3619	(0.83)
	20	4.6350	(1.00)	4.4800	(0.97)	3.9292	(0.85)
	30	5.5620	(1.00)	5.5070	(0.99)	4.7226	(0.85)

V. *Concluding Remarks*

After launching the EU ETS, the EU carbon market has grown rapidly and is now regarded as the key instrument of the European Commission's climate change program to reduce greenhouse gas emissions. However, transaction costs may limit the potential beneficial effects of the carbon emission trading market, by reducing trading volume and frequency while increasing abatement costs. Although the emission trading market is becoming mature, transaction costs remain significantly large. In this paper, we allow for the effect of transaction costs to explore the regime-dependent nonlinear mean reversion behavior of carbon prices in the EU ETS.

To figure out the effect of the transaction costs, we use the threshold VECM. The empirical results evidence regime-dependent nonlinear adjustment to the equilibrium relationship. We also evaluate the forecasting performance of the threshold VECM and compare it to that of the linear VECM. The accuracy of the threshold VECM forecast is found to be superior to that of the linear VECM, especially when predicting carbon futures prices. Our results suggest that transaction costs affect the mean reversion process and restrain market efficiency and price discovery in the EU ETS.

Our study does not account for the relationship between the carbon price and macroeconomic variables such as energy prices and production activity as Chevallier (2011) has suggested. The analysis of market efficiency and price discovery in the carbon market should be extended to the general setting of macroeconomic model. Also, our analysis may be extended to other pollution allowances. As Jaraitė *et al.* (2010) argued, transaction costs vary with firm size, and thus an analysis of market efficiency at the firm level may provide useful results. We leave these studies for future research.

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