Market Efficiency and Price Discovery in the EU Carbon Futures Market

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ABSTRACT

We examine the issues of market efficiency and price discovery in the European Union carbon futures market. Our findings suggest that none of the three carbon futures contracts examined here are priced according to the cost-of-carry model, although two of the three contracts form a stable long-run relationship with the spot price and interest rates, and hence act as adequate risk mitigation instruments. In terms of information diffusion between the futures and spot contracts, it appears that the spot and futures markets share information efficiently and contribute to price discovery jointly. However, our analysis suggests that the predominant source of information spillovers appears to be the sign or direction of price change, i.e. return spillover, rather than the magnitude of price change, i.e. volatility spillover.

Keywords: Carbon-Dioxide Allowances, Futures, Cost-of-Carry, Price Discovery, Market Efficiency, Cointegration, Granger Causality, Volatility Spillover, Global Warming.

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1. Introduction

In this paper we address three questions related to the efficiency of carbon allowances traded under the European Union Emissions Trading Scheme (EU ETS). First, we ask if there is a stable long-run relationship between the EU ETS carbon spot price, EU ETS carbon futures price and interest rates. This question is of fundamental importance because it asks if the carbon futures are useful hedging instruments. If the answer to this question is yes, we then proceed to test a stronger assumption by asking the following: Is the long-run link between the spot and futures prices given by a no-arbitrage cost-of-carry model? Within this framework we also test for the existence of convenience yield obtained by holding a spot position. Lastly, we address the issues of price discovery by analysing information spillovers between the cash and futures prices by seeking to uncover which market leads the carbon price discovery process. This is, to our knowledge, a first empirical investigation of market efficiency and price discovery in this emerging and rapidly developing market that according to the World Bank's latest report[1] tripled in the past year, from US$10 billion in 2005 to US$30 billion in 2006.

Climate change is a major challenge faced by the international community. The effects of human-caused greenhouse gases and global warming are becoming increasingly visible from record temperatures to rising sea levels. In economic terms the Stern review (Stern, 2006) reports that, in the absence of policy action, climate change is likely to reduce world GDP by between 5 percent and 20 percent permanently. In contrast, the cost of acting to reduce greenhouse gas emissions is estimated to be around 1 percent of world GDP. In an attempt to slow down and stabilise the pace of climate change, most countries, excluding the US and Australia[2], have signed and ratified the Kyoto Protocol (UNFCC, 1998) to the UN Framework Convention on Climate Change (UNFCCC).

[1] The World Bank: State and Trends of the Carbon Market 2007.
[2] As of May 2007. However, these countries have implemented their own state mandatory/voluntary carbon trading systems.

Based on a “cap and trade” system, the Protocol sets targets for the reduction of greenhouse gases (GHG), and facilitates the trading of permits to emit GHGs between countries and individual entities. The existence of a trading mechanism allows most GHG abatement to occur in those sectors of the economy in which it is cheapest – achieving the cap with the lowest possible economic impact. So far, several international markets for carbon permits have emerged, with the European Union Emissions Trading Scheme (EU ETS) being at the forefront in terms of both the market size and its regulatory organisation.

While the existing literature on carbon markets provides theoretical arguments for and against such schemes (e.g. Cooper; 1996; Klepper, Peterson and Springer, 2003; McKibbin, Ross, Shackleton and Wilcoxen 1999, MKibbin and Wilcoxen, 2006) the effectiveness of any existing carbon trading scheme will rely on the ability of the market mechanism to produce prices which accurately reflect the true marginal costs of GHG abatement. In this context, the important issue of market efficiency and price discovery in carbon *derivative* markets also arises. Derivative products, such as futures and options facilitate risk mitigation through reassignment of risk between economic agents of different risk preferences. However, a necessary condition for effective risk management, i.e. transfer of risk, is the existence of a long-run link between spot price and derivative prices (futures price in our case) that is achieved through an equilibrium pricing relationship. If such a link did not exist the spot and futures prices would diverge by assuming independent stochastic paths and the futures position, that is supposed to mitigate price risk, would instead result in additional risk exposure. Thus, an independent (inefficient) futures market has a potential to undermine the efficacy of any carbon trading scheme and should be tested for.

Our empirical methodology includes a cointegration analysis of spot and futures carbon prices and interest rates as well as Granger causality and volatility spillover tests.

We also present a method for measuring and testing for convenience yield within the framework of cointegration. Our dataset consists of the European Union carbon emission allowance (EUA) spot and futures prices and interest rates over the June 2005 – November 2006 time period. In our empirical approach we track three futures contracts with expiry dates in December 2006, December 2007 and December 2008 through time, matching their time to expiry with interest rates of equal maturity. We opt for this approach due to the relative novelty and uniqueness of the EU ETS market in which long time series on nearby futures contracts do not exist but where long-term futures contracts are traded in a relatively liquid market.

As Brenner and Kroner (1995) show using a no-arbitrage model the existence of cointegration between spot and futures prices depends on the time-series properties of the cost-of-carry. In particular, if interest rates have a stochastic trend, spot and futures prices will not be cointegrated by themselves. We use this result and after testing unit root in the price series we conduct tests of trivariate cointegration between the carbon cash and futures prices and interest rates. Our tests indicate the existence of stable long-run links between the carbon cash price, interest rates and the price of the December 2006 and December 2007 futures contracts. However upon testing for parameter restrictions within the cointegrating relationships, we find that neither of these two contracts' prices is consistent with the cost-of-carry model. While the December 2006 contract does not seem to be dependent on the level of interest rates, the relation between the December 2007 contract and interest rates is different from that predicted by the pricing model. The violation of the cost-of-carry relation can be interpreted as an indicator of market inefficiency and points to arbitrage opportunities in this market although each of these two futures contracts can be used effectively for hedging purposes.

The futures contract that expires in December 2008 does not exhibit a stable long-run relationship with the spot price. We attribute this finding to the unavailability of a relevant carbon spot price for the Phase II of the EU Emissions Trading Scheme. Briefly, the EU ETS is implemented in two stages: Phase I (2005-2007) and Phase II (2008-2012). Unused carbon allowances from Phase I are not expected to be valid in Phase II and will expire at the end of 2007[3]. Therefore, the December 2008 contract is not expected to be cointegrated with the current spot price but instead acts as a vehicle of price discovery for the future Phase II spot price.

We for the existence of convenience yield associated with owning a spot contract compared with a futures position and find some evidence of convenience yield in the December 2007 futures contract pricing equation; no convenience yield in the December 2006 contract equation and we are unable to conduct the test on the December 2008 contract because of the lack of a cointegrating relation between this contract and the cash contract. Thus, our evidence suggests possible existence of convenience yield in certain market segments although this finding should be interpreted with care because our tests are based on the assumption of the cost-of-carry model.

Toda and Yamamoto (1995) Granger causality tests indicate that, in two out of the three cases examined here, there is bi-directional Granger causality between the spot and futures prices. This can be interpreted as evidence of a price discovery process that occurs in both the spot and futures market, a finding inconsistent with evidence from other commodity markets, in which the futures price serves as a vehicle of price discovery. We also find that the spot and future carbon returns exhibit autoregressive conditional heteroscedasticity (ARCH), i.e. a time-varying risk profile, and we test for transfers of risk (volatility spillovers) between the spot and futures contracts. Our findings suggest that there are no statistically significant risk spillovers between the December 2006 futures contract and the spot price, bi-directional spillovers between the December 2007 futures and the spot contracts, and no volatility spillovers between the December

[3] See Section 4 for more detail.

2008 contract and the spot price. We interpret these finding as evidence that information is shared between the spot and futures carbon markets, but that the information contained in the sign or direction of market movement (i.e. return spillover) is more readily transmitted than the information representing the magnitude of price change (i.e. volatility transfer).

Overall, it seems that the EU ETS futures market provides a means for effective risk management and contributes to the price discovery process in the spot market. However, it also appears that this relatively new market exhibits a number of idiosyncrasies relative to developed markets, most notable of which is the lack of the cost-of-carry relationship between its spot and futures prices.

The rest of this paper is organised as follows. We present a theoretical framework for pricing futures contracts as well as the hypotheses we wish to test in Section 2. This section also contains a brief literature survey of relevant issues. In Section 3 we describe the main characteristics of the European Union carbon allowances considered in this paper and outline our econometric method. Our empirical findings are presented in Section 4 and we conclude with Section 5.

2. Theoretical and Empirical Links between Spot and Futures Prices

In theory, and for assets that allow arbitrage between spot and futures markets, futures contracts can be priced according to a no-arbitrage cost-of-carry model. If $F_{t,T}$ is the current price of a futures contract that expires in $(T-t)$ years[4] and S_t is the current spot price, the cost-of-carry relation links the spot and futures prices in the following way:

$$F_{t,T} = S_t e^{(r_t-\delta)(T-t)} \tag{1}$$

[4] $(T-t)$ is calculated as the number of days to expiry date divided by 360.

where r_t is a risk-free interest rate and δ can be thought of as either a dividend yield in case of a dividend paying stock or a convenience yield in case of a commodity. The cost-of-carry model thus posits that the futures price should equal the spot price, adjusted for the opportunity cost of holding a spot position, i.e. the interest foregone, less a dividend/convenience yield. Because the cost-of-carry model is derived from a no-arbitrage condition that results in a risk-free portfolio (see for example Hull, 1997), the relevant discount rate (r_t) is the risk-free rate.

The convenience yield in Eq. (1) is typically interpreted as the value of privilege of holding a unit of inventory, e.g. to be able to meet unexpected demand or to keep a production process running. Since the convenience yield is defined within the framework of a pricing model, it is difficult to test for its existence in isolation of conducting a test of the pricing model itself. Although the literature has attempted to address this and other issues concerning convenience yield tests (e.g. Dusak, 1973; Carter, Rausser and Schmitz, 1983; and Fortenbery and Hauser, 1990) there is no consensus or clear empirical evidence that would suggest the existence or otherwise of convenience yield (Zapata and Fortenbery, 1996).

In this paper, we provide a method for testing for the existence of convenience yield that is based on a cost-of-carry relationship. Further, we put forward and test a new hypothesis relating to EU ETS carbon contracts, which proposes that a convenience yield may exist in the pricing formula for longer maturity futures contracts but should be zero in the last year of any EU ETS carbon contract's life. Thus in a way we propose a hypothesis of a term structure of convenience yields. The rationale behind our hypothesis is a market regulation under which EU ETS affected installations settle their carbon obligations. Specifically, the affected firms are required to surrender their carbon permits for emissions produced over a calendar year all at the same time, in the month of April of the following calendar year. Thus, a spot permit will differ from a futures permit whose time to expiry is less than one year only to the extent of the time value of money. We hypothesise this to be true because such futures contracts will be converted into spot positions prior to the settlement month of April and will thus fulfil the role of spot contracts in terms of offsetting carbon obligations. On the other hand, the industry may obtain convenience from holding a cash position relative to a futures contract that expires at a date following the settlement month of April. These futures contracts cannot be used as offsets of current carbon obligations directly but must be sold on the market and a spot contract acquired in order to settle any EU ETS carbon liability.

In a perfectly efficient and frictionless market the pricing relationship expressed in Eq. (1) should hold at every instant over a futures contract life (Stoll and Whaley, 1990). However transaction costs and other market imperfections create a no-arbitrage price interval within which we can expect the futures prices to fluctuate. MacKinlay and Ramaswamy (1988) list a number of factors that can drive the futures price away from its theoretical value. For example, stochastic interest rates result in arbitrage positions that are usually risk free becoming risky due to unanticipated interest earnings/costs associated with the marking to market activity. Further, futures contracts with longer times to maturity incorporate more risk associated with unanticipated changes in the dividend/convenience yield. Chung (1991) notes that there may also exist other forms of risk premium associated with the cost-of-carry model. For example, attempting to exploit observed deviations from the no-arbitrage bounds can, ex ante, prove to be risky due to order execution lags. That is, traders are not guaranteed execution of their orders at the observed prices. Chung shows that once execution lags and transaction costs are taken into account, the size and frequency of boundary violations are substantially smaller than those reported by other studies. In summary, the pricing error from the cost-of-carry relation can be expected to fluctuate between some no-arbitrage boundaries as follows:

$$b_{L,t} < \left(F_{t,T} - S_t e^{(r_t - \delta)(T-t)} \right) < b_{U,t} \qquad (2)$$

where $b_{L,t}$ and $b_{U,t}$ represent lower and upper no-arbitrage interval bounds created by the above mentioned factors.

The above arguments thus suggest that the no-arbitrage condition, as given in Eq. (1), would hold in the long-run but not necessarily in the short-term when applied to an imperfect market with frictions such as transaction costs, stochastic interest rates, et cetera. After taking natural logarithms Eq. (1) can be expressed as a cointegrating relation of the following form:

$$f_t = s_t + r_t\left(T-t\right) - \delta\left(T-t\right) + u_t \tag{3}$$

where $s_t \equiv \ln S_t$, $f_t \equiv \ln F_t$ and u_t is a stationary zero-mean innovation term whose variance is determined by the extent of market imperfections. Note also that the terms in brackets of the above equation represent reverse time trends that start at *T* (years to maturity) and end at zero as *t* approaches *T*. In order to test the cost-of-carry model we can re-write Eq. (3) as:

$$\begin{aligned} f_t &= as_t + b\left(r_t\left(T-t\right)\right) - \delta\left(T-t\right) + \eta_t \\ &= -\delta T + as_t + b\left(r_t\left(T-t\right)\right) + \delta t + \eta_t \end{aligned} \tag{4}$$

and test the following hypotheses:

H.1. Eq. (4) forms a cointegrating relationship, i.e. η_t is stationary.

H.2. $H_0 : a = b = 1$ i.e. restrictions implied by the cost-of-carry model.

The above hypotheses *H.1.* and *H.2.* have the following interpretations. Should we find that both *H.1.* and *H.2.* hold then there exists a long-run relationship between the spot and futures carbon prices and the interest rates that is consistent with the cost-of-carry model. This finding would imply that the futures market is efficient and that there are no arbitrage opportunities between the spot and futures prices. Futures contracts would also be a suitable risk mitigation instrument. An alternative finding would be to discover that

H.1. holds while the hypothesis *H.2.* does not. In this situation, Eq. (3) would represent a cointegrating relationship but we would conclude that while the three markets are linked in the long-run, the relationship is not provided by arbitrage activity and hence arbitrage opportunities persist in the market. However, even though arbitrage opportunities may exist in this case, the finding of a long-run relation (with or without the cost-of-carry restrictions) implies that futures contracts can still be regarded as an adequate instrument for risk management. Lastly, failure to find any kind of long-run relation would imply two things. First, it would mean that the futures contract price is independent of the underlying spot price and thus should not be used for hedging. Second, it would mean that there are arbitrage opportunities in this market.

Besides testing the above hypotheses we are also in a position to estimate the convenience yield parameter δ and test the zero-convenience yield, using the following test:

H.3. $H_0 : \delta = 0$ for $(T-t) < 1$

At the time of writing this paper, only the December 2006 futures contract was eligible for this test.

2.1 A Review of Empirical Evidence

Previous empirical tests of the cost-of-carry model come in two flavours: tests of the lead-lag relationship between spot and futures prices and tests of market efficiency as given by the pricing relation in Eq. (1). The two strands of literature are closely related and complement each other on the basis of the Granger Representation Theorem (Engle and Granger, 1987). In particular, when a futures contract is priced efficiently the futures and the underlying spot prices will be linked through Eq. (1), that is they will be cointegrated. In this case, the Granger Representation Theorem states that there will also be a lead-lag relationship between the two prices. While the empirical evidence is mixed, it appears that futures prices lead/Granger cause spot prices and that the cost-of-carry model holds in the market for most financial assets but not all commodities.

MacKinlay and Ramaswamy (1988) investigate deviations from the cost-of-carry pricing of the S&P 500 index and index futures. They use intraday 15 minute data and find that the departures from the cost-of-carry relationship (i.e. mispricing) increase with time even after controlling for non-synchronous trading. Harris (1989) uses the same data over a ten-day period surrounding the October 1987 stock market crash. He reports that non-synchronous trading of constituent stocks explains some but not the entire large futures-cash basis (price difference) observed during the crash. In commodity markets, Bessler and Covey (1991) examine the US cattle markets and report some evidence of cointegration between the cash and nearby futures prices. Schroeder and Goodwin (1991) fail to find cointegration between the spot and futures contracts for live hogs while Fortenbery and Zapata (1993) find cointegration between corn and soybeans spot and futures contracts. Zapata and Fortenbery (1996) also find cointegration for most storable commodities and suggest that previous findings of no cointegration are based on an inappropriate specification due to omission of interest rates from the cointegrating relationships.

Testing for the lead-lag effect between futures and spot prices, Figuerola-Ferretti and Gilbert (2005) and Fontenbery and Zapata (1997) find that futures prices lead the cash markets while a number of studies suggests otherwise. For example, Green and Joujon, (2000) find evidence that the French CAC-40 spot index leads its futures contract and Silvapulle and Moosa (1999) report bi-directional non-linear Granger causality between futures and spot prices in the crude oil market. Quan (1992) examines the price discovery function in the crude oil market and finds that the futures market does not contribute significantly to the price discovery process. However, Schwarz and Szakmary

(1994) argue that Quan's model is mis-specified and that oil futures dominate in price discovery.

3. Data Description

Our study is primarily concerned with the relationship between the spot and futures prices of carbon allowances traded under the European Union Emissions Trading Scheme (EU ETS). The European Union allowances (EUAs) are allocated to carbon emitting installations in quantities predetermined by the EU member state governments and trade on both over-the-counter markets and organised exchanges. The trading occurs between firms that over-emit and under-emit relative to their allocations as well as other market participants such as speculators and arbitrageurs. The EUAs are legally biding and the affected installations are required to surrender permits for emissions produced each calendar year in the month of April, of the following year. If an insufficient number of permits is surrendered, the affected institution is charged a penalty and is still liable to surrender the deficit permits. Thus the penalty does not represent an upper limit of the price of carbon emissions.

The EU ETS itself is designed to operate in two phases. Phase I (2005-2007) is a pilot program that is expected to prepare the EU for compliance with the Kyoto Protocol. The EU ETS is expected to achieve full compliance with the Kyoto Protocol over the course of Phase II. Although some EU member countries have suggested that unused Phase I permits will be valid GHG offsets in Phase II, the general opinion is that the two are inconsistent and that Phase I permits will expire at the end of 2007.

Our dataset consists of daily observations on interest rates, carbon allowance spot prices and December 2006, December 2007 and December 2008 carbon futures contracts. We use spot EUA prices collected from Powernext[5] energy exchange while the futures

[5] www.powernext.com

carbon contracts trade on the European Climate Exchange (ECX)[6]. The data on short-term Euribor interest rates and longer term swap rates is obtained from DataStream. In order to match the interest rate maturity to the maturity of each of the futures contracts effectively, i.e. track the futures contracts through time, we interpolate the interest rates to maturities of every month within the data sample. For example, we match a two-year futures contract with a two-year swap interest rate during the first month of the contract's life, a twenty-three month interest rate in the second month of the contract's life and so on. The time period covered is 24 June 2005 – 27 November 2006. Figure 1 depicts the evolution of the spot and futures prices over this time period.

Figure 1: Spot and Futures Time Series in natural logarithms: Jun 05 – Nov 06.

We make two observations about the above graph. First, although the four series exhibit nonstationary behaviour they appear to move in a relatively loose union. This observation supports our empirical modelling technique (i.e. cointegration framework) outlined in Section 4. The exception is the December 2008 futures contract that departs from the common trend at the end of 2005. The second observation is that we see a sharp decline in all four price series over the period 24 April 2006 – 12 May 2006. The decline coincides with the release of the first official carbon emissions report that showed lower

[6] www.ecx.com

than expected carbon emissions over the 2005 reporting period. Thus, we will need to be careful to account for this break in our empirical model.

4. Model Specification and Empirical Findings

If there is a cointegrating relationship between the carbon spot price s_t, the carbon futures price f_t and an interest rate variable r_t there will also exist a Vector Error Correction Model (VECM) relating the three variables (Engle and Granger, 1987). Further, if we want to allow for structural breaks and trend breaks the VECM model can be written as[7]:

$$\Delta \mathbf{Y}_t = \boldsymbol{\alpha} \begin{pmatrix} \boldsymbol{\beta} \\ \boldsymbol{\gamma} \end{pmatrix}' \begin{pmatrix} \mathbf{Y}_{t-1} \\ t\mathbf{D}_{t-k} \end{pmatrix} + \boldsymbol{\mu} \mathbf{D}_{t-k} + \sum_{i=1}^{k-1} \boldsymbol{\Gamma}_i \Delta \mathbf{Y}_{t-i} + \sum_{i=0}^{k-1} \boldsymbol{\kappa}_i \mathbf{I}_{t-i} + \boldsymbol{\varepsilon}_t \tag{5}$$

where $\mathbf{Y}_t' = (s_t, f_t, r_t)$, t is a time trend, $\mathbf{D}_{t-k}$ is a vector of intervention dummy variables and $\mathbf{I}_{t-i}$ is a vector of indicator dummy variables. In the above specification $\boldsymbol{\varepsilon}_t$ is assumed to be an independent and identically distributed (3×1) vector stochastic process with zero mean and a variance matrix $\mathbf{H}$. In case where the three series are found to be cointegrated we will use the above specification to test for Granger Causality using Toda and Yamamoto (1995) tests[8]. However, should we find no evidence of cointegration between the futures and spot carbon prices and interest rates Granger Causality tests will be conducted in a VAR model in first differences.

Additional to the above causality tests we also test for volatility transmissions (i.e. volatility spillovers) between the spot and futures contracts. We model the conditional variance matrix $\mathbf{H}_t$ of the spot and futures return vector process $(\Delta s_t \quad \Delta f_t)'$ using a BEKK(*1,1*) multivariate GARCH specification (Engle and Kroner, 1995):

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[7] See Johansen, Mosconi and Nielsen (2000) for the formulation of the VECM in the presence of structural breaks.

[8] Toda and Yamamoto show that having chosen a VECM of lag length *k-1* we can test for causality in a VAR model specified in levels where the lag length is *k+d*, *d* being the maximal order of integration of any process in the system.

$$\mathbf{H}_t = \mathbf{\Gamma}'\mathbf{\Gamma} + \mathbf{\Lambda}' e_{t-1} e_{t-1}' \mathbf{\Lambda} + \mathbf{\Phi}' \mathbf{H}_{t-1} \mathbf{\Phi} \quad (6)$$

where $\mathbf{\Gamma}$ is an upper triangular (2×2) matrix while $\mathbf{\Lambda}$ and $\mathbf{\Phi}$ are (2×2) matrices of parameters. Thus, our last set of hypothesis tests takes the following form:

H.4. The spot market does not transmit volatility to the futures market $H_0 : \lambda_{22} = 0, \phi_{22} = 0$.

H.5. The futures market does not transmit volatility to the spot market $H_0 : \lambda_{21} = 0, \phi_{21} = 0$

4.1. Cointegration Tests

As noted above, the price series appear to exhibit nonstationary behaviour, i.e. contain a unit root. We test this hypothesis more formally using unit root tests with and without structural breaks. All series were found to have a unit root in log levels, while the first log differences are stationary at the 1% level.[9]

Next we test for cointegration, i.e. a long-run relationship between the futures price, the spot price and the interest rates. In our study we need to take particular care of accounting for possible trends and/or breaks predicted by the cost-of-carry model as well as visual analysis of the raw data in Figure 1. Potentially we have three breaks to model.

First, there is a level shift in all series related to price declines in April 2006 (the settlement month of the first year of carbon trading). Such a level shift is easy to model by including indicator dummies for the relevant observations. Second, a break associated with our hypothesis of zero-convenience yield in the last year of any carbon futures life needs to be included. This break was only applicable to the December 2006 contract at the time of writing this paper. For this case two sub-samples need to be considered: the first sub-sample from 24 June 2005 to 20 December 2005 and the second sub-sample

[9] The unit root tests are available from the authors upon request.

from 3 January 2006 to 27 November 2006. Third, a graphical representation of the mis-pricing relationship as given by Eq. (2) and presented in Appendix 1 suggest that all three futures contracts have undergone structural shifts in their relation to the spot contract in December 2005, i.e. the end of the first compliance period. It seems that market participants have significantly altered their expectations about the carbon price following this period. The same sub-samples as defined earlier will need to be considered. Thus we can anticipate a difficulty in separating the effects of the structural break associated with the end of the 2005 reporting period and the zero-convenience yield hypothesis for the December 2006 contract.

In order to test for cointegration in the presence of the three breaks/shifts we use Johansen, Mosconi, and Nielsen (2000) maximum likelihood cointegration test method. This method generalizes the likelihood-based cointegration analysis developed by Johansen (1988, 1991) to the case where structural breaks exist at known points in time as in Eq. (5). We consider that some or all of the time series follow a trending pattern in each sub-sample and the cointegrating relations are trend stationary in each sub-sample; a trend break is allowed both in the cointegrating relations and in the variables in levels. A level shift is also allowed. The VECM in Eq. (5) is estimated with $\mathbf{D}_t = (1, D_{1t})'$ where

$$D_{1,t} = \begin{cases} 1 & \text{if January } 1^{st} \text{ } 2006 \leq t \leq T \\ 0 & \text{otherwise} \end{cases} \tag{7}$$

Correspondingly indicator dummies for the break points can be defined:

$$I_t = \begin{cases} 1 & \text{for t } = \text{ first observation after January } 1^{\text{st}} \text{ } 2006 \\ 0 & \text{otherwise} \end{cases} \tag{8}$$

We also include additional indicator dummy variables[10] that correspond to the observations around the end of April 2006. The risk-free interest rate was found to be

[10] Since these dummies are indicator dummies they do not affect the critical values of the usual cointegration tests.

weakly exogenous for all three contracts, therefore the cointegration tests are conducted under this assumption. The number of lags k is chosen so as to minimise the Schwartz criterion and the autocorrelation tests on $\boldsymbol{\varepsilon}_t$. We summarise the results of the Johansen, Mosconi, and Nielsen (2000) cointegration tests in Table 1[11] and conclude that the December 2006 futures and spot prices and interest rates are cointegrated with one cointegrating vector. Similarly, December 2007 futures and spot prices and interest rates are cointegrated with one cointegrating vector but December 2008 futures price, the spot price and interest rates are not cointegrated.

Table 1: Cointegration Rank Tests

Hypothesis	Trace Statistic	p-value*	95% simulated critical value	95% critical value Osterwald-Lenum (1992)
December 2006: Model with a Trend Break				
$R = 0$	73.071	0.000	35.845	25.731
$R \leq 1$	12.963	0.228	18.478	12.448
December 2007: Model with Trend Break				
$R = 0$	74.771	0.000	32.785	25.731
$R \leq 1$	11.272	0.272	17.135	12.448
December 2008: Model with Trend Break				
$R = 0$	22.964	0.482	34.779	25.731
$R \leq 1$	6.936	0.721	18.513	12.448

Johansen, Mosconi, and Nielsen (2000) tests for cointegration between a carbon futures contract, the spot price and interest rates. * p-value for the simulated distribution.

4.2. Market Efficiency Tests

We model the long-run relationship between the December 2006 futures price, the spot price and the interest rates by specifying a cointegrating vector that includes a linear trend restricted to the cointegrating relationship and a trend break dated from January 2006 until the end of the sample. The results are presented in Table 2.

[11] We conduct cointegration analysis in CATS in RATS version 2 (Dennis, 2006).

Table 2. The Long-Run Models for December 2006 futures, spot, interest rates

The Cointegrating Vector (t-ratios in parentheses)	
f	1
s	-1.003 (-256.774)
r	-0.750 (-0.811)
t	0.017 (1.668)
$tD_{1,t-k}$	-0.002 (-0.117)
The speed of Adjustment Coefficients (t-ratios in parentheses)	
s	0.375 (-1.041)
f	-0.686 (-1.742)

H.1. LR test on the cost-of-carry restrictions: H_0: a = b = -1, χ^2 statistic = 0.469 , p-value =[0.791]

H.3. LR test on the restriction that the coefficient of the trend is equal to minus the trend break coefficient: χ^2 statistic = 0.359, p-value = [0.549].

The cointegrating relationship takes the form given in Eq. (4) augmented with a dummy variable $D_{1,t}$ which can be re-written as $f_t - as_t - b\left(r_t\left(T-t\right)\right) - \delta t - \delta_2 tD_{1,t-k+1} = \eta_t$.

The first restriction we would like to test involves the coefficients on the interest rate and the spot price variables, i.e. *H.1*. Although we cannot reject this hypothesis based on a joint likelihood ratio (LR) test presented in the above table, we argue that this finding is most likely due to the large standard error associated with the interest rate variable. In particular, according to the estimates presented in Table 2 the interest rate variable is not different from zero at any conventional level of significance, implying that interest rates do not play a role in the cost-of-carry relation. This is clearly inconsistent with the theory of arbitrage and we thus conclude that the cost-of-carry model does not hold in this case. The coefficients of the trend variables which measure the magnitude of convenience are not significantly different from zero either. These findings imply that the convenience yield, δ in equation (4), is zero over the whole sample, with the dummy variable showing no difference between the first part of the sample and the post January 2006 period. However, given that the structural break identified in the previous section occurs at about the same point in time, it is difficult to interpret our results concerning the convenience yield parameter. We thus cautiously conclude that although the December 2006 futures contract price, the spot contract price and the risk-free interest rate are linked in the long-run, the long-run relation is not given by a cost-of-carry model.

Table 3 presents estimates of the cointegrating relationship between December 2007 futures contract, the spot futures price and interest rates.

Table 3. The Long-Run Model: December 2007 futures, spot, interest rates

The Cointegrating Vector (t-ratios in parentheses)	
f	1
s	-0.991 (-135.013)
r	-3.053 (-4.906)
t	0.111 (-5.836)
$tD_{1,t-k}$	-0.077 (-3.075)
The speed of Adjustment Coefficients (t-ratios in parentheses)	
s	-0.084 (-0.405)
f	-0.689 (-3.380)

H.1. LR test on the cost-of-carry restrictions: H_0: a = b = -1, χ^2 statistic = 9.073 , p-value = [0.011]

H.3. LR test on the restriction that the coefficient of the trend is equal to minus trend break coefficient χ^2 = 4.178, p-value = [0.041]

The cointegrating relationship takes the form given in Eq. (4) augmented with a dummy variable $D_{1,t}$ which can be re-written as $f_t - as_t - b\left(r_t\left(T-t\right)\right) - \delta t - \delta_2 tD_{1,t-k-1} = \eta_t$.

In the case of the December 2007 carbon futures contract the cost-of-carry restriction is strongly rejected. We again conclude that although there is a long-run link between the December 2007 futures price, the spot price and interest rates, the link is not given by the cost-of-carry model. Judging by the statistical significance of the coefficients on the time trend variable we can conclude that there is a statistically significant convenience yield associated with this contract, which becomes smaller following December 2005 but does not disappear completely. This is in line with our hypothesis in which the convenience yield is expected to disappear only after December 2006, i.e. with the start of the last year of this contract's life.

Since our cointegration tests indicate that there are no long-run links between the December 2008 futures contract, the spot contract and the interest rates we only present Granger causality and volatility spillover analysis for this futures contract.

4.3 Granger Causality and Volatility Spillover Tests

We now turn to Toda and Yamamoto (1995) Granger Causality tests, which will shed light on the price discovery process in the market for carbon permits. Table 4 summarises these test results.[12]

Table 4. Granger Causality Tests

Null Hypothesis	Chi-Squared (4) test statistic	p-value
Spot is not caused by Dec 2006 Futures ^	27.325	0.000
Dec 2006 Futures is not caused by Spot ^	14.289	0.014
Spot is not caused by Dec 2008 Futures ^	24.419	0.000
Dec 2008 Futures is not caused by Spot ^	27.141	0.000
Spot is not caused by Dec 2008 Futures *	11.201	0.024
Dec 2008 Futures is not caused by Spot *	3.003	0.557

* Implemented using a VAR model in first difference including intercept break but no trend/trend break.

^ Implemented as Toda and Yamamoto (1995) Causality Tests

There is strong statistical evidence, at a significance level below 5 percent, of bi-directional Granger causality between December 2006 carbon futures contract and the carbon spot price as well as between December 2007 futures price and the spot price. On the other hand, we find that the spot return is Granger caused by the information content provided by December 2008 futures contract but not vice versa. Given these findings it is interesting to note December 2008 futures contract is a derivative instrument on a currently non-existent EU ETS Phase 2 spot price.

[12] Causality tests conducted using Mosconi and Giannini's (1992) gave the same results. These tests are derived by explicitly applying the cointegration restrictions both under the null and the alternative hypotheses.

In contrast with these results, the volatility spillover tests presented below suggest that in two out of the three cases there are no statistically significant volatility transfers.

Table 5. Volatility Spillover Tests

Volatility Spillover	ARCH	GARCH
Spot to Dec 2006 Futures	0.002 (0.010)	-0.047 (-0.125)
Dec 2006 Futures to Spot	0.222 (0.725)	0.020 (0.049)
Spot to Dec 2007 Futures	1.096 (9.351)	-0.397 (-2.418)
Dec 2006 Futures to Spot	-0.681 (-9.341)	0.124 (1.003)
Spot to Dec 2008 Futures	0.066 (0.793)	-0.054 (-1.177)
Dec 2008 Futures to Spot	0.016 (0.191)	-0.073 (-1.069)

T-ratios (in brackets) are calculated using Bollerslev-Wooldridge (1992) robust standard errors.

In particular, while we can see that volatility spills over, in both directions, between the December 2007 futures contract and the spot price, there are no statistically significant spillover coefficients between the December 2006 contract and the cash price and between the December 2008 futures and spot prices.

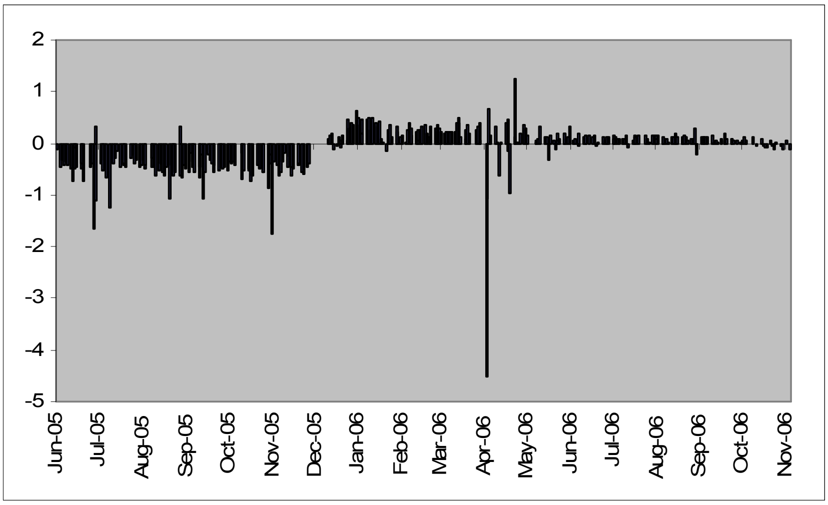
5. Conclusion

In this paper we examined the issues of information diffusion and market efficiency in the European Union carbon allowance market. Our findings indicate that none of the carbon futures contracts studied here are priced according to the cost-of-carry model. These findings suggest the existence of arbitrage opportunities in the EU ETS market and should be tested further. Although the December 2006 and December 2007 prices do not adhere to the cost-of-carry model, they are found to form long-run links with the carbon spot price and interest rates. On the other hand, the December 2008 contract does not form such a relation. We thus argue that the 2006 and 2007 futures contracts are effective risk mitigation instruments of carbon price risk in Phase 1 of EU ETS, while the 2008 futures contract is not.

We also find evidence of time varying risk profiles in all carbon contracts. Specifically, Granger causality and volatility spillover tests imply that although there are information spillovers between all three futures carbon contracts and the spot price, the predominant content of spillovers appears to be the sign or direction of price change, i.e. return spillover, rather than the magnitude of price change, i.e. volatility spillover.

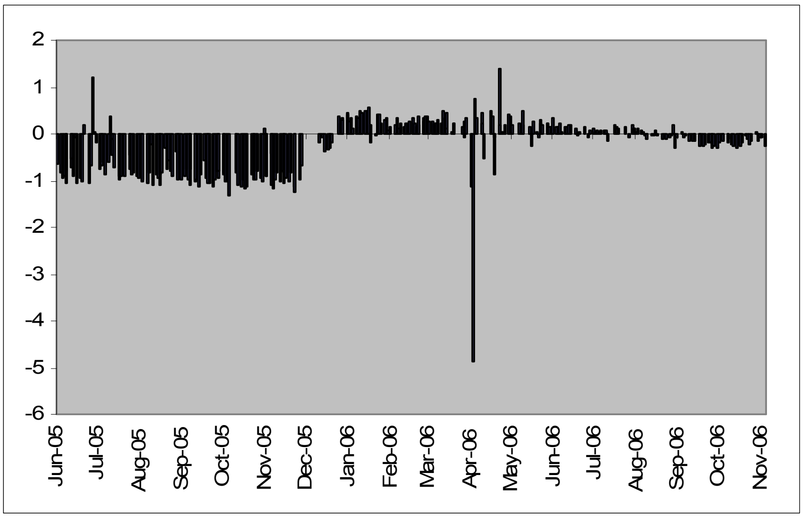
Appendix 1: Empirical Mispricings from the Cost-of-Carry Model

Figure A.1: Mispricing Relationship – December 2006 carbon futures contract



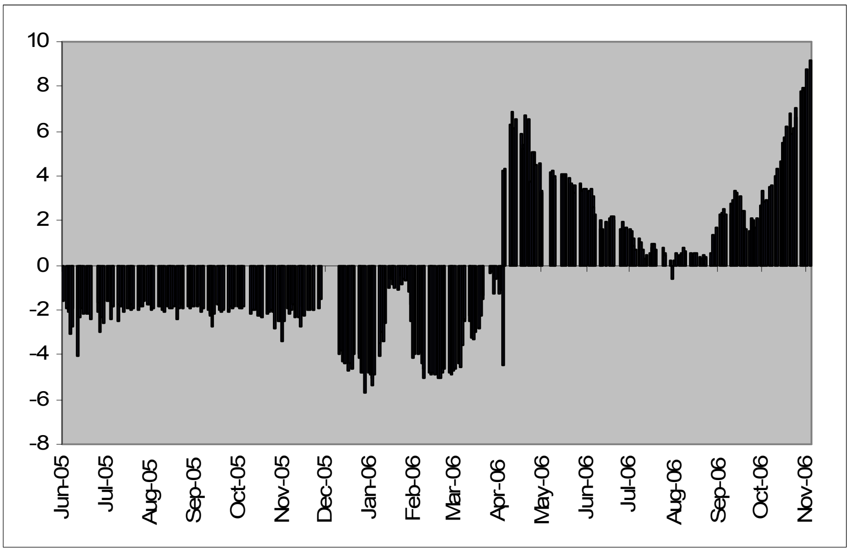
Mispricing is defined as a deviation of the realised futures price from its cost-of-carry price given by $Mispricing_t = F_{t,T} - S_t e^{(r_t - \delta)(T-t)}$.

Figure A.2: Mispricing Relationship – December 2007 carbon futures contract



Mispricing is defined as a deviation of the realised futures price from its cost-of-carry price given by $Mispricing_t = F_{t,T} - S_t e^{(r_t - \delta)(T-t)}$.

Figure A.3: Mispricing Relationship – December 2008 carbon futures contract



Mispricing is defined as a deviation of the realised futures price from its cost-of-carry price given by $Mispricing_t = F_{t,T} - S_t e^{(r_t - \delta)(T-t)}$.

References

Bessler, D.A. and Covey, T. (1991), "Cointegration: Some Results on U.S. Cattle Prices", *Journal of Futures Markets*, **11(4)**, 461-474.

Beveridge, S., and Nelson, R. C. (1981). "A new approach to decomposition of economic time series into permanent and transitory components with particular attention to measurement of the 'Business Cycle'", *Journal of Monetary Economics* **7**, 151-174.

Bollerslev, T. and Wooldridge, J. M. (1992), "Quasi-maximum Likelihood Estimation and Inference in Dynamic Models with Time-varying Covariances", *Econometric Reviews*, **11(2)**, 143-172.

Brenner, R. J. and Kroner, K. F. (1995), “Arbitrage, Cointegration, and Testing the Unbiasedness Hypothesis in Financial Markets”, *The Journal of Financial and Quantitative Analysis* **30(1)**, 23-42.

Carter, C. A., Rausser, G. C. and Schmitz, A. (1983). “Efficient Asset Portfolio and the Theory of Normal Backwardation.” *Journal of Political Economy,* **91**, 319–331.

Chan, K. (1992). A further analysis of the lead-lag relationship between the cash market and stock index futures market. *Review of Financial Studies* , **5**, 123-152.

Chan, K.C. and Karolyi G.A. (1991), ‘An empirical comparison of alternative models of the short term interest rate’, *The Journal of Finance*, **XIVII(3)**.

Cooper, R. (1996) A Treaty on Global Climate Change: Problem and Prospects.

Dennis, J.G. (2006) *CATS in RATS: Cointegration Analysis of Time Series*, distributed worldwide by Estima, Evanston, Illinois, USA.

Dickey, D.A. and Fuller, W. A. (1979), “Distribution of the estimators for autoregressive time series with a unit root”, *Journal of the American Statistical Association*, **74**, 427-431.

Dusak, K. C. (1990), "Futures Trading and Investor Returns: An Investigation of Commodity Market Risk Premiums," *Journal of Political Economy*, **81**, 1387-1406.

Engle, R. F. and Granger, C.W. (1987), “Co-Integration and Error Correction: Representation, Estimation, and Testing”, *Econometrica*, 55(2), 251-276.

Engle, R. F. and Kroner, K. (1995), ‘Multivariate simultaneous GARCH’, *Econometric Theory* **11**, 122-150.

Fiquerola-Ferretti and Gilbert (2005),”Price variability and marketing method in non-ferrous metals”, *Resources Policy*, **27(3),** 169-177

Fortenbery, T. R. and Hauser, R. (1990), "An Examination of Futures Contract Investment Potential." *American Journal of Agricultural Economics*, **72,** 721-726.

Fortenbery, T.R. and Zapata, H.O. (1993). "An Examination of Cointegration Relations between Futures and Local Grain Markets." *Journal of Futures Markets*. **13(8)**, 921-932.

Green C.J. and Joujon , E.(2000), "Unified tests of causality and cost of carry, the pricing of the French stick index futures contract", *International Journal of Finance and Economics*, **5(2)**, 121-140.

Gonzalo, J. and Granger, C. (1995)' Estimation of common long-memory components in co integrated systems', *Journal of Business and Economic Statistics*, **13 (1)**, 22-35.

Harris, L. (1989), "S&P 500 Cash Stock Press", *Journal of Finance*, **44(5)**, 1155-1175.

Hasbrouck, J. (1995), "One security, many markets: Determining the contributions to price discovery", *The Journal of Finance*, **I(4).**

Hull, J. (1997), *Options, Futures, and Other Derivatives*, Prentice Hall, Upper Saddle River, NJ

Johansen, S. (1988), "Statistical Analysis of Cointegration Vectors", *Journal of Economic Dynamics and Control,* **12**, 231-54.

Johansen, S. (1991), "Estimation and Hypothesis Testing of Cointegration Vectors in Gaussian Vector Autoregressive models", *Econometrica,* **59**, 1551-1580.

Johansen, S., Mosconi, R. and B. Nielsen (2000), "Cointegration Analysis in the Presence of Structural Breaks in the Deterministic Trend", *Econometrics Journal,* **3**, 216-49.

Klepper, G., S. Peterson, K. Springer. (2003). DART97: A Description of the Multi-regional, Multisectoral Trade Model for the Analysis of Climate Policies. Kiel Working Papers 1149. Kiel Institute for World Economics. Kiel.

Kwiatkowski, D., Phillips, P. C. B., Schmidt, P. and Shin, Y. (1992), “Testing the null of stationarity against the alternative of a unit root: How sure are we that the economic time series have a unit root?”, *Journal of Econometrics* 54, 159-178.

McKibbin W., Ross M, Shackleton R., Wilcoxen P.J. (1999) “Emission trading, capital flows and the Kyoto Protocol”, *The Energy Journal*, Special Issue: The costs of the Kyoto Protocol, pp. 287-334

McKibbin W. and Wilcoxen P.J. (2006) “A Credible Foundation for Long Term International Cooperation on Climate Change”, Lowy Institute for International Policy Working Paper No. 1.06

MacKinlay, A.C, and Ramaswamy, K. (1988) "Index-Futures Arbitrage and the Behavior of Stock Index Futures Prices." *Review of Financial Studies*, **1**, 137-158.

Mosconi, R. and Giannini, C, 1992. "Non-causality in Cointegrated Systems: Representation Estimation and Testing," *Oxford Bulletin of Economics and Statistics*, vol. **54(3)**, 399-417.

Ng, N. (1987), “Detecting spot forecasts in futures prices using causality tests”, *Review of Futures Markets* , **6**, 250-267.

Osterwald-Lenum, M. (1992), “A Note with Quantiles of the Asymptotic Distribution of the ML Cointegration Rank Test Statistics”, *Oxford Bulletin of Economic and Statistics,* **54**, 461-472.

Quan, J. (1992), “Two-step testing procedure for price discovery role of futures prices”, *Journal of Futures Market*, **12**, 139–149.

Schroeder, T.C. and Goodwin, B.K. (1991), "Price discovery and cointegration for live hogs", *Journal of Futures Markets*, **11(4)**, 685-96.

Schwarz, T.V. and Szakmary, A.C. (1994). “Price discovery in petroleum markets: Arbitrage cointegration and the time interval of analysis”, *Journal of Futures Markets* **(14)**, 147-167.

Silvapulle, P. and Moosa, I. A. (1999). "”The relationship between the spot and futures prices: Evidence from the crude oil market”, *Journal of Futures Markets*, **19**, 175–93.

Stern, N. (2006), Stern Review on the economics of climate change, HM Treasury

Stock, J. H. and Watson, M, W. (1988), “Testing for Common Trends”, *Journal of the American Statistical Association*, **83,** 1097-1107.

Toda, H.Y. and Yamamoto, T. (1995), “Statistical inference in vector autoregression with possibly integrated processes”, *Journal of Econometrics*, **66**, 225-250.

The World Bank. (2007), State and State and Trends of the Carbon Market 2007, http://carbonfinance.org/docs/Carbon_Trends_2007-_FINAL_-_May_2.pdf

Zapata, H.O. and Fortenbery, T. R. (1996), “Stochastic Interest Rates and Price Discovery in Selected Commodity Markets”, *Review of Agricultural Economics,* **18(4)**, 643-654.