Price Discovery and Liquidity in the European CO_2 Futures Market: An Intraday Analysis

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Abstract

European Union CO_2 allowances (EUAs) are traded on several markets with increasing intensity. We provide an intraday data analysis of the EUA futures market for the complete first trading period 2005-2007 (Phase 1). To investigate the trading process in this young market, we compare the two main trading platforms, ECX and Nord Pool, with respect to price discovery and liquidity. Both are of high relevance to traders. We analyze liquidity by estimating traded bid-ask spreads following the approach of Madhavan, Richardson, and Roomans (1997) and study price discovery using the VECM framework of Engle and Granger (1987).

We find that while estimated transaction costs are always lower on the larger exchange ECX, the less liquid platform Nord Pool also contributes to price discovery, especially during the first months of trading. Overall, results indicate that from 2005 to 2007 liquidity in the European CO_2 futures market has markedly increased and according to microstructural criteria the trading process has developed smoothly.

JEL-Classifications: G13, G14, G19.

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1 Introduction

With the official start of the European Union Greenhouse Gas Emission Trading Scheme (EU ETS) in January 2005, a new European commodity market has been created. In the market for European Union Allowances (EUAs), purchasing one EUA entitles the holder to emit one ton of CO_2 equivalent greenhouse gases. With an increasing range of new instruments (e.g. spot, forwards, futures and warrants) the carbon market has steadily gained complexity. Currently, the EU ETS is the largest CO_2 trading scheme world wide. While prices from the OTC market have served as reference prices at the beginning of the EU ETS, their importance has declined with the development of standardized carbon products on distinct trading platforms.[1] During the first trading period, which lasted from 2005 to 2007, organized allowance trading has been fragmented across the five trading platforms European Climate Exchange (ECX), Nord Pool, Powernext, European Energy Exchange (EEX) and Energy Exchange Austria (EXAA). Since the underlying asset being traded is equal on all exchanges, questions with respect to price discovery and liquidity migration across trading platforms are important factors to investigate both for traders and platform providers.

The end of the first trading period of the EU ETS in December 2007 provides an excellent opportunity to address these questions and to give a comprehensive overview of the European carbon market development. Being the first to have access to intraday transactions data, we are able to complement the existing literature by investigating this very recent market from a microstructure angle. Since almost all trading takes place in the futures markets, we focus on futures price data supplied by ECX and Nord Pool, the two most liquid European trading exchanges for futures EUAs. The aim of the paper is twofold. Apart from providing an overview of the development of trading on both exchanges, we compare two microstructure issues that are of high relevance to potential traders: liquidity and price discovery. With respect to liquidity, we start by comparing overall trading volumes as well as the development of trading frequencies across exchanges. We then estimate traded bid-ask spreads following the approach of Madhavan, Richardson, and Roomans (1997) that allows the estimation of spreads when no quote data but only transaction data and trade indicator variables are available. Applying this procedure has the advantage that it enables us to infer main causes of trading frictions and, hence, transaction costs. To analyze relative price discovery on both exchanges we use the VECM framework by Engle and Granger (1987) building on the cointegration relationship between transaction price series. To quantify the two markets' relative contributions to the price discovery process we apply two different measures: common factor weights proposed by Schwarz and Szakmary (1994) and information shares as introduced by Hasbrouck (1995).

[1] For instance, the calculation of the carbon price index used by Mansanet-Bataller, Pardo, and Valor (2007) was stopped in line with the introduction of exchange traded European carbon futures on the European Energy Exchange (EEX), which have been serving as a daily reference price since then.

Our analysis is related to a vast body of market microstructure literature that investigates liquidity and price discovery on financial markets. Regarding the European carbon market, there is no literature analyzing bid-ask spreads. A few studies have addressed the question of price discovery between spot and futures markets (Seifert, Uhrig-Homburg, and Wagner, 2006; Daskalakis, Psychoyios, and Markellos, 2006; Milunovich and Joyeux, 2007), but no work has investigated price discovery between futures prices on distinct exchanges. Since almost all trading volume takes place in futures markets, we believe our study to be of high relevance. Furthermore, the mentioned studies only use daily data, possibly blurring results of price leadership if price discovery takes place at finer trading intervals.

We believe that our results are of interest for regulatory authorities that are in charge of the design of the upcoming commitment periods, for operators of exchange platforms, for researchers interested in the application of microstructure tools to new markets and, equally important, for agents who trade actively in the market like market makers, brokers, arbitrageurs, etc. It is also possible to use our results in order to evaluate the relative developments of the markets. From the public, a lot of criticism has been raised about the market in Phase 1 mainly due to the significant over-allocation of EUAs. Academic work like Daskalakis and Markellos (2007) and Milunovich and Joyeux (2007) using data until the end of 2006 conclude that weak form informational efficiency in the European CO_2 market is violated and that a cost-of-carry relation does not hold for spot and futures prices. Our evidence shows that trading frictions in forms of transaction costs have decreased over the first trading phase, trading volume has increased and price discovery takes place across exchanges. Hence, it appears that from a trading perspective, the market has made a lot of progress in the last three years and operates in a rather mature way.

The remainder of the paper is organized as follows. Section 2 introduces the reader briefly to the organization of the European carbon market and to the institutional details that are relevant for the data collection procedure. Section 3 describes the methodology of the bid-ask spread analysis by Madhavan, Richardson, and Roomans (1997) and its econometric application. The price discovery process using an error correction model by Engle and Granger (1987) is detailed in Section 4. Estimation results for both types of analysis are displayed subsequent to the description of the methodology. The paper ends with an interpretation of the results and a conclusion with respect to the future of the organized carbon market in Section 5.

2 Market Structure and Data

2.1 Market Structure

As was stated, the EU ETS started in January 2005 as a central instrument for member states of the European Union to achieve the emission reduction targets of the Kyoto Protocol in a cost-effective way.[2] It covers over 10,000 installations in the energy and industrial sectors that are collectively responsible for about 50% of European CO_2 emissions. Trading is organized in several stages. The first trading period served as a pilot phase and covers the years 2005-2007 while the second trading period from 2008-2012 constitutes the Kyoto commitment period (Phase 2). Plans for the post Kyoto trading period 2013-2020 (Phase 3) became more concrete after the United Nations summit in Bali in December 2007. Besides, in January 2008 the European Commission has agreed on a so called "Climate and Energy Package", which makes first regulatory suggestions and improvements for the continuation of action against climate change in the EU.

The EU ETS is organized as a cap-and-trade scheme where participating firms have to reduce the amount of emitted CO_2 and to annually demonstrate that their level of EUAs corresponds to their actual emissions. Every year, at the end of February, a certain amount of EUAs is allocated to the compliant firms for the current trading year according to the National Allocation Plans (NAPs). On April 30 of the following year, firms have to deliver the required EUAs to the national surveillance authorities according to their actual emissions volume. Not handing in the required amount of emissions is fined with an extra fee of Euro 40 (Euro 100) per missing EUA in the pilot period (Phase 2) additional to delivering the missing amount of EUAs.

Companies being able to keep emissions below their allocation level are free to sell excess allowances in the market. Firms which need additional allowances to comply with their output levels have the choice to either invest in emissions-reducing technologies, to switch to less emissions-intensive production technologies or, if marginal abatement costs are higher than the market price of EUAs, to buy EUAs on the European CO_2 market.

Within the pilot and commitment periods surplus allowances can be transferred for use during the following year (banking). Banking between Phase 1 and Phase 2 was forbidden by most of the countries. Only France and Poland allowed for restricted banking. As allocation always takes place in February, borrowing of EUAs from the future year is indirectly possible as the compliance date for the preceding year is April 30. However, it was not possible to borrow EUAs between 2007 and 2008.[3] Trading is organized as bilateral, over-the-counter (OTC) and organized exchange trading. It takes the form of agency or proprietary trading and may be for compliance, speculative or arbitrage

[2]On an EU-wide level, emissions have to be reduced by 8% in the first Kyoto commitment period 2008-2012 relative to the output level of 1990.

[3]Note consequently that there exist essentially two spot markets, one for the pilot and one for the first commitment period (Seifert, Uhrig-Homburg, and Wagner, 2006).

Table 1:
Overall trading volume of the EUA Spot and futures market in the Phase 1 (2005-2007)

Year	Spot [Mio t CO_2]	Futures [Mio t CO_2]
2005	10.25	110.82
2006	49.53	508.29
2007	60.26	1 062.42

purposes.

To get an overview of how many allowances have been exchanged among market agents, Table 1 displays the total trading volumes split into futures and spot activities since the EU ETS has been operating and includes both OTC and exchange trading for all existing carbon instruments. It can be seen that overall trading volume markedly increased from 120 Mio t CO_2 in 2005 to 1 123 Mio t CO_2 in 2007. The share of spot relative to overall trading volume declined from 8.5% to 5.4%.

Carbon Exchanges

In trading Phase 1, organized EUA trading took place at five exchange platforms. ECX only offers futures, Powernext and EXAA only offer spot trading whereas on EEX and Nord Pool both instrument types can be traded. In the following analysis we focus on the two main trading venues ECX and Nord Pool which comprise by far the largest exchange traded futures volume: In 2006, ECX being a member of the Climate Exchange Plc group possessed a market share of 86.5%. The Norwegian platform Nord Pool had a share of 12.5%, see also Daskalakis, Psychoyios, and Markellos (2006). In terms of overall market share, in early 2007 ECX accounted for 56% of EUA trading volume, being followed by OTC trading volume with 42%.

The traded futures instruments on both platforms are standardized contracts giving the holder the right and the obligation to buy or sell a certain amount of European Union Allowances of carbon dioxide at a certain date in the future at a pre-determined price. On both exchanges, one futures contract ('lot') corresponds to 1 000 EUAs and hence delivers the right to emit 1 000 tons of carbon dioxide equivalent. The contracts allow users to lock in prices for delivery of carbon emission allowances (EUAs) at given dates in the future with delivery guaranteed by the respective clearing house. Counterparty risk is mitigated by specific margin requirements. The contracts are promoted to be designed to facilitate trading, risk management, hedging and physical delivery of EUAs. While contracts with monthly expiry and annual contracts with expiry in March exist, we focus on the by far most liquid annual contracts with expiry in December. These contracts expire on the first business day of December on Nord Pool and on the last Monday of December on

ECX.[4] Settlement is three days after the last trading day. On both exchanges, trading is organized as continuous trading with trading hours from 08:00 to 18:00 CET on ECX and from 08:00 to 15:30 CET on Nord Pool. The minimum tick size is Euro 0.01 per ton on both exchanges. Trading and clearing fees per contract amount to Euro 3.50 on ECX and to Euro 3.00 on Nord Pool. The annual fee for full members is Euro 2 500 on ECX and Euro 3 000 on Nord Pool. Both exchanges have introduced market makers to boost liquidity, order types include limit orders, market orders and iceberg orders.[5]

2.2 Data Set and Summary Statistics

In the following analysis we use intraday transactions data for annual standardized futures and forward contracts being traded from April 22, 2005 to December 28, 2007 on ECX and from February 11, 2005 to December 28, 2007 on Nord Pool. After providing some summary statistics to show the market development on both platforms, we briefly address some data collection issues that result from investigating data from two distinct markets.

Table 2 depicts exchanged trading volumes of EUA futures with expiry in December (without OTC) for both platforms disaggregated by years and contracts. It can be seen that trading volume has markedly increased both over years and over contracts, but to a higher extent on ECX compared to Nord Pool. Highest trading activity takes place in the nearby futures contract. The development of the Dec07 contract in 2007 is an exception and is due to the publication of large EUA over-allocation in April 2006, which led to a marked price decline (compare also Figure 1 showing the development of futures prices on the European carbon market for Phase 1). Due to lack of liquidity, for the rest of the paper we only consider the Dec05 to Dec08 contracts and disregard those with later expiry, i.e. Dec09 to Dec12.

Figures 2 and 3 depict the daily transaction frequencies and the average monthly standard deviation of daily returns for each platform and contract. Again, it can be inferred that transaction frequencies are highest for the nearby contract and hence markedly increase in December of the year prior to expiry. If we compare volatility across contracts and exchanges we observe a high volatility in the market where the respective contract is launched first. For the Dec05 and Dec06 contracts there are two peaks that disturb the relatively smooth volatility pattern, one in July 2005 for the Dec05 contract and one in April/May 2006 for Dec06 contract. The first one probably relates to large price fluctuations as a consequence of unexpected selling in the market by some Eastern European countries that succeeded to obtain access to the carbon market earlier than anticipated by market participants. Maybe it also reflects overall insecurity with respect to price drivers as a consequence of the terrorist attacks in London in July 2005. The second

[4]If there is a public holiday in the respective trading week, the prior Monday is taken, the procedure continues until there is no public holiday in the trading week.

[5]Information is obtained from the official websites www.europeanclimateexchange.com and www.nordpool.no as of February 2008.

Table 2:
Trading volumes (without OTC) of EUA futures with expiry in December at ECX and Nord Pool broken down into contract and year

Year	Contract	ECX		Nord Pool	
		Mio t CO_2	Mio Euro	Mio t CO_2	Mio Euro
2005	Dec05	22.96	522.79	6.76	139.89
	Dec06	6.78	151.88	1.91	41.86
	Dec07	1.93	43.91	1.05	23.39
	Dec08	0.49	10.46	0	0
	Dec09-Dec12	0.02	0.43	0	0
	Sum	32.18	729.47	9.72	205.14
2006	Dec06	93.77	1 763.93	9.92	182.47
	Dec07	35.25	520.51	1.25	19.66
	Dec08	29.56	540.10	0.37	6.87
	Dec09-Dec12	0.46	9.16	0	0
	Sum	159.04	2 833.7	11.54	209
2007	Dec07	50.24	65.22	3.10	4.03
	Dec08	258.96	5 237.18	18.38	380.78
	Dec09-Dec12	29.44	652.86	0.25	5.41
	Sum	338.64	5 955.26	21.73	390.22

peak can be clearly linked to the market breakdown when the significant over-allocation of EUAs became public at the end of April 2006.[6] Consequently, the Dec07 contract became worthless to the firms as they were not allowed to transfer excess EUAs from 2007 into 2008. This price decline translates into high return volatility in the year 2007, especially in the last months of trading when price variations of Euro 0.01 were very high compared to a price level of about Euro 0.03. Finally, for the Dec08 contract, except for the high volatility at the launch of the contract at both platforms, the volatility pattern is smooth. Comparing the two figures, it can be observed that often trading intensity increases in times of high market volatility.

Data Collection

When investigating the development of bid-ask spreads and price discovery on both exchanges, we have to address some issues related to the differences in trading protocols and contract specifications as well as some standard high frequency issues. To start with, for both types of analysis, we omit overnight returns that could induce heteroskedasticity into our data set. Then, for comparing bid-ask spreads across exchanges over the whole trading period of contracts, we omit non-overlapping trading intervals and focus only on periods when the respective contract was traded on both exchanges. We furthermore aggregate all trades within the same second that have the same trade indicator to ac-

[6]Compare the weekly newsletter at *www.climatecorp.com.*

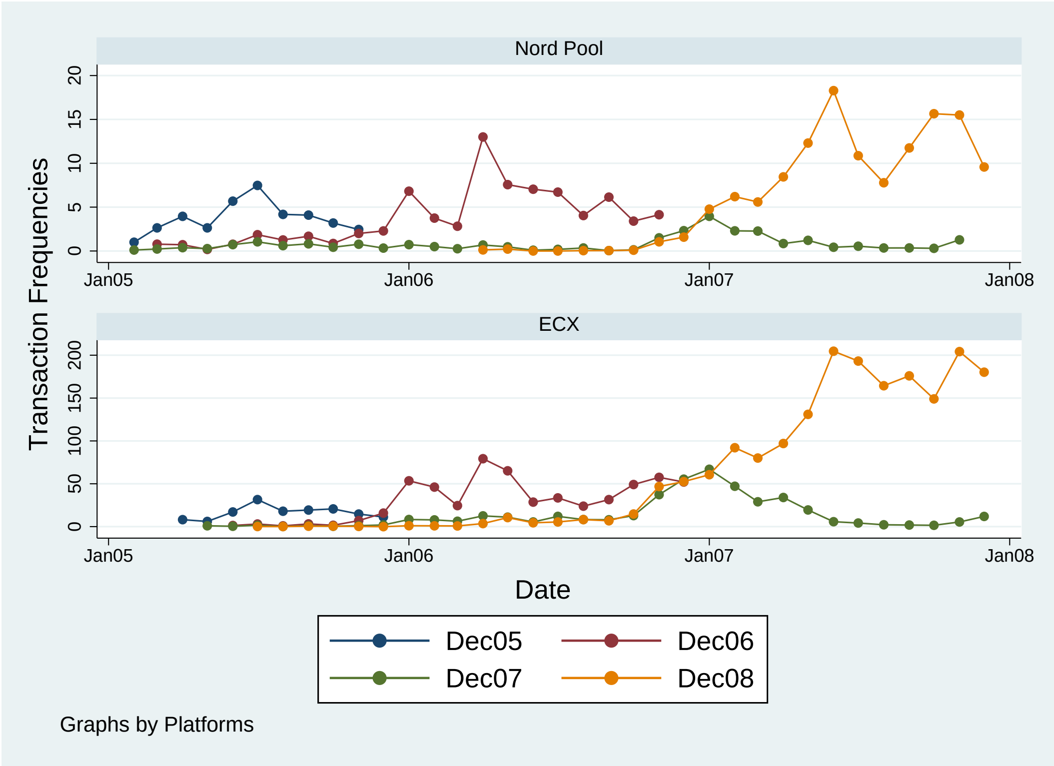
Figure 1:
EUA futures prices for the Dec05 to Dec08 contracts in Phase 1 at ECX

count for price effects of orders walking up or down the book. Finally, we only include data from continuous trading periods into our analysis and hence exclude pre-opening and post-closing prices.

Regarding the price discovery analysis, some further re-organization of the data set is necessary prior to estimation. First, in order to synchronize trading hours we delete ECX trades that occur after 15:30. Thus, throughout the paper we only use data from 08:00 until 15:30 CET. Second, in our price discovery analysis we postulate a one-to-one relationship between the prices of futures contracts traded on different markets. However, that relationship does not exactly hold due to differing expiration dates on both exchanges. Hence, in order to establish an equilibrium price relation across exchanges, we discount all contracts to their present value at the respective trading day.[7] The third and probably most important aspect that has to be considered is the question of price synchronization. Transactions do not occur at regular intervals, nor do transactions in the two parallel trading platforms take place simultaneously. Explicitly, our data includes much more transaction prices for ECX than for Nord Pool. Thus several futures prices have to be eliminated from the series. To synchronize the two price series, we form three different

[7]We mainly use monthly interest rates for discounting and linearly interpolate interest rates between months. Interest rate data is obtained from Datastream. For very short discounting horizons, we use EONIA interest rates, for horizons up to a year we use Euribor interest rates and for horizons of more than one year we employ European monthly corporate interest swap rates.

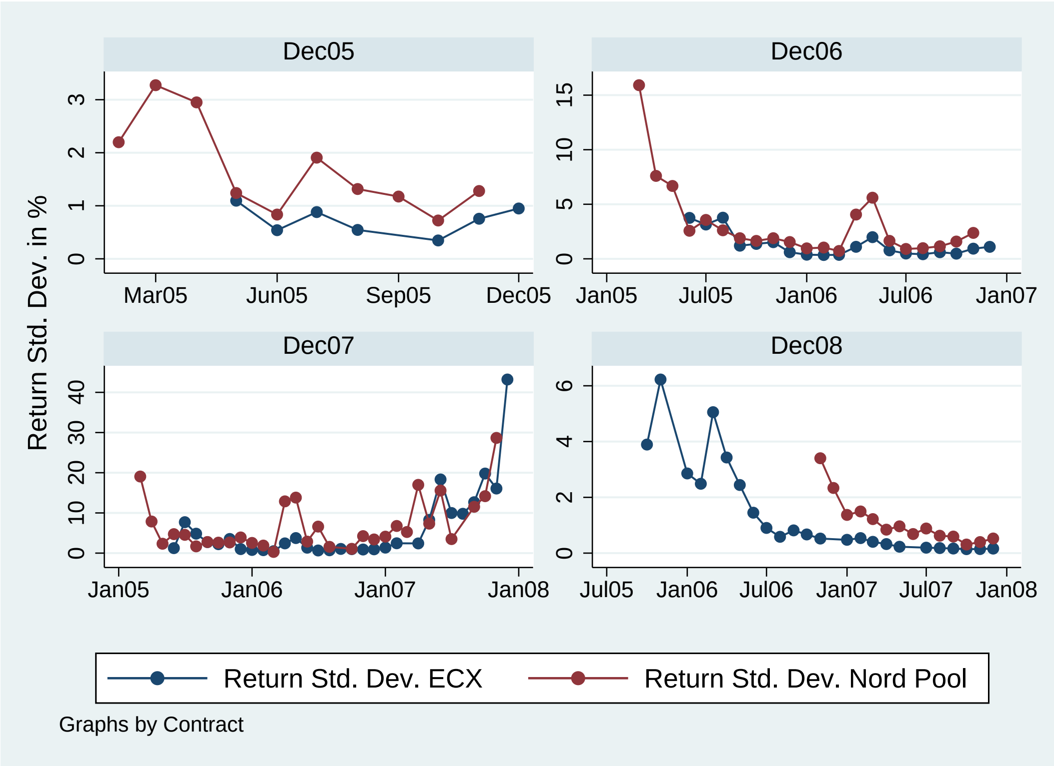
Figure 2:
Monthly transaction frequencies for the Dec05 to Dec08 contracts in Phase 1 at ECX and Nord Pool



data sets of matched trade pairs. First, beginning at the start of each trading day, for every transaction price at Nord Pool we identify the most recent transaction price at ECX. These pairs are saved and generate the price series for our model (NP-Match). This method favors Nord Pool, the less liquid exchange. Estimation results that systematically use "stale" prices of ECX are likely to underestimate the role of ECX and are hence a very conservative measure for price leadership of ECX. If, contrary to expectations, we find a large share of price discovery at Nord Pool, these results might stem from the fact that we systematically favor Nord Pool. It is easy to inquire the robustness of this type of findings by applying an analogous synchronization procedure favoring ECX (ECX-Match). The third possibility not clearly favoring one exchange over the other has been suggested by Harris, McInish, Shoesmith, and Wood (1995).[8] The authors synchronize the data as follows. Beginning at the start of each trading day, as soon as a trade has taken place on both exchanges the trade which has occurred latest in time is matched with the most

[8] Another possibility of synchronization is the use of equidistant time intervals. This procedure consists of matching the last observed prices at the end of pre-specified time intervals (e.g. 5 minutes, 30 minutes) in each market. If no price updating has taken place within one time interval then the most recent price that occurs in the respective market is used for the matching. In our analysis we do not consider this matching approach as the probability that the most recent price comes from the more liquid market, which is in our case ECX, is high. Consequently, ECX would be favored compared to Nord Pool as a relatively new ECX trade would be probably matched with an older Nord Pool price.

Figure 3:
Monthly average return standard deviation at Nord Pool and ECX for the respective trading period of each contract, Dec05 to Dec08



recent trade on the other exchange. This pair is saved and a new matched trade pair is formed in the same manner for the whole data sample (Harris-Match).[9] Obviously, for the Harris-Match the frequency of the data is determined by the market with the fewest trades, which is in our analysis Nord Pool.

Since we expect price discovery to take place at the larger and more liquid trading platform ECX, we opt for choosing the NP-Match dis-favoring ECX as a benchmark and refer to other matching algorithms as a robustness check.

Before estimating bid-ask spreads on both exchanges, one remark may be in place. In the upcoming analysis, we apply microstructure tools that are known to work well in developed markets to a very young market. Hence, conditions to apply these tools may be in some instances not optimal, e.g. with respect to the number of observations. More general, benefits of applying microstructure analysis over investigations using daily data might depend upon the time interval and contract under examination. Fortunately, most investigations generate sensible results in the European CO_2 market which may be of interest for researchers considering the application of similar tools in other emerging markets.

[9]Compare Harris, McInish, Shoesmith, and Wood (1995), pp. 566. This matching procedure is referred to as "REPLACE ALL".

3 Spread Analysis

In this section, we investigate the development of transaction costs on both exchanges for Phase 1. We measure transaction costs by estimating bid-ask spreads, which are defined as the difference between the best quoted ask and the best quoted bid price in the market. This measure can be interpreted as the costs of trading a round-trip (i.e. costs paid by a liquidity demander to a liquidity supplier for an instantaneous buy and sell transaction) or alternatively as the price concession that it takes to induce an agent waiting in the market to transact immediately instead of waiting until prices move in her favor. The existence of a bid-ask spread and hence of trading frictions is typically explained with the existence of order processing costs, inventory costs or asymmetric information costs.[10]

As examples for the latter in the carbon market, one can think of firms' private decisions that concern for instance the start-up, closure or expansion of new and old installations as well as private news about market entrants. Furthermore, market participants might have different incentives and possibilities to acquire information about e.g. market developments (current and future market scarcity, abatement costs and potential of other firms) and about regulatory issues (National Allocation Plans for upcoming trading phases, development of CER market, incorporation of other trading schemes into the EU ETS). It is reasonable to assume that big companies that are more affected by the ETS have better sources of information than smaller firms. This potential for asymmetric information influences market scarcity and thus the market price for EUAs or project based EUAs (CERs).[11]

Since we do not have access to best ask and bid quotes, bid-ask spreads cannot be calculated immediately from the data. Fortunately however, the market microstructure literature has proposed a variety of procedures to estimate the spread and its components. Given that our data set identifies transactions as either buyer-initiated or seller-initiated, we can use a so called trade indicator model to estimate and compare traded spreads on ECX and Nord Pool.

3.1 Methodology

Trade indicator models assume that information about the underlying asset is contained in the order flow. They use this variable in form of a binary trade initiation indicator to model short-run dynamics of quotes and transaction prices and to estimate traded

[10] Order processing costs include costs like telecommunications costs or exchange fees that have to be paid by the liquidity provider. Inventory costs arise for risk-averse liquidity suppliers that bear the risk of having to build up unwanted inventory positions to accommodate public order flow. Asymmetric information costs arise if traders with private information are active in the market and trade on their information. In order to balance losses to informed traders, liquidity providers may charge a spread. Compare also the surveys by Madhavan, Richardson, and Roomans (1997) and Biais, Glosten, and Spatt (2005).

[11] Additional to EUAs, a market for Certified Emissions Reductions (CERs) - assets, which arise from energy-reducing projects in developing countries - has been created.

spreads. Trade indicator models have been proposed by e.g. Glosten and Harris (1988), Huang and Stoll (1997) and Madhavan, Richardson, and Roomans (1997). Since we observe a significant degree of autocorrelation in our trade initiation variable, we opt for the GMM-approach suggested by Madhavan, Richardson, and Roomans (1997) that does not restrict autocorrelation in the order flow to be zero. One potential drawback of this approach is the assumption of a constant trade size. Since median trade size is equal across exchanges, we believe that the model can be applied to our setup.

Let P_t denote the transaction price of our underlying futures contract at time t, x_t is a trade indicator variable with $x_t = 1$ if the transaction at time t is buyer-initiated and $x_t = -1$ if it is seller-initiated.[12] We assume that purchases and sells are (unconditionally) equally likely, so that $E[x_t]$=0 and Var$[x_t]$=1. We assume that beliefs about the asset value might change due to new public information announcements that are not associated with the trading process and due to the order flow that provides a noisy signal about the future value of the underlying asset. The innovation in beliefs between $t-1$ and t from dissemination of public information is denoted by η_t which is an i.i.d. random variable with mean zero and variance σ_η^2. Buy (sell) orders are considered as a noisy signal about an upward (downward) revision in beliefs given that there are some traders with private information in the market. We assume that the revision in beliefs (or price impact) $\theta \geq 0$ is positively correlated with the innovation in order flow $x_t - E[x_t|x_{t-1}]$, such that the change in beliefs due to order flow is $\theta(x_t - E[x_t|x_{t-1}])$. Finally, let μ_t stand for the post-trade expectation of the "true" value of the stock conditional on public information and on the information revealed by the trade initiation variable. μ_t evolves according to

$$\mu_t = \mu_{t-1} + \theta(x_t - E[x_t|x_{t-1}]) + \eta_t. \tag{1}$$

We assume that the price generating process P_t is determined from the unobserved process (1) by adjusting for the costs of providing liquidity services ϕ_t (order processing costs, baseline inventory costs or mark-ups from non-competitive pricing). ϕ captures the non-permanent (transitory) effect of order flow on prices. Quotes are ex-post rational and are conditional on the trade initiation variable being a buy or a sell order, such that a bid-ask spread emerges ($P_t^a = [P_t|x_t = 1] > P_t^b = [P_t|x_t = -1]$):

$$P_t = \mu_t + \phi x_t + \xi_t = \mu_{t-1} + \theta(x_t - E[x_t|x_{t-1}]) + \phi x_t + \eta_t + \xi_t, \tag{2}$$

with ξ_t being an independent and identically distributed random variable with mean zero. To estimate Equation (2), we need to make assumptions about the dynamic behavior of the order flow. We assume a general Markov process for the trade indicator variable where $\gamma = Pr[x_t = x_{t-1}|x_{t-1}]$ denotes the probability that a trade at the ask (bid) follows a trade at the ask (bid). Positive serial correlation in the order flow arises for a variety of reasons such as the breaking up of orders or price continuity rules, leading

[12] Compare Madhavan, Richardson, and Roomans (1997), pp. 1039.

to $\gamma > 0.5$. Let ρ denote first order autocorrelation of the stationary trade indicator variable x_t, i.e. $\rho = E[x_t x_{t-1}]/Var[x_t]$. It is straightforward to show that $\rho = 2\gamma - 1$ such that autocorrelation in the order flow is an increasing function of the probability of a continuation. In order to estimate Equation (2), we need to compute $E[x_t|x_{t-1}]$, i.e. the conditional expectation of the trade initiation variable given public information. It can be easily seen that $E[x_t|x_{t-1}] = \rho x_{t-1}$.[13] Now we only have to substitute out the unobservable belief μ_{t-1} of Equation (2) to obtain an estimable equation. We can do so by noting that $\mu_{t-1} = P_{t-1} - \phi x_{t-1} - \xi_{t-1}$ and obtain

$$P_t - P_{t-1} = (\phi + \theta)x_t - (\phi + \rho\theta)x_{t-1} + e_t, \tag{3}$$

where $e_t = \eta_t + \xi_t - \xi_{t-1}$. In the absence of asymmetric information and transaction costs, the price follows a random walk process. In the presence of frictions, movements in the price P_t reflect order flow and noise induced by price discreteness as well as public information news. From Equation (3), we see that the implied bid-ask spread at time t is equal to $P_t^a - P_t^b = 2(\phi + \theta)$.[14]

3.2 Estimation Approach

Analog to Madhavan, Richardson, and Roomans (1997), we estimate Equation (3) by GMM as an elegant way to account for autocorrelation of the error term and for possible conditional heteroskedasticity. We estimate the model using standard orthogonality conditions and make use of the definition of the autocorrelation parameter $\rho = E[x_t x_{t-1}]/Var[x_t]$ as an additional constraint to separately identify our two parameters of interest θ (asymmetric information component) and ϕ (transitory spread component).

3.3 Estimation Results

This section contains the results of GMM estimations of Equation (3) for different contracts traded on ECX and Nord Pool. In order to obtain comparable results for the overall trading periods, we estimate the model using observations starting from the calender month in which we have observations for both exchanges to the last common trading day of the contracts. As stated before, we also exclude overnight returns.[15] We furthermore only report results for estimations with at least 150 observations. To get a first intuition on liquidity at both exchanges at the contract level, Table 3 provides an overview of estimated half spreads in Euro, $\hat{s}/2 = \hat{\phi} + \hat{\theta}$, for each instrument estimated over the whole sample period.

[13] Since $E[x_t|x_{t-1} = 1] = Pr[x_t = 1|x_{t_1} = 1] - Pr[x_t = -1|x_{t_1} = 1] = \gamma - (1 - \gamma) = \rho$ and analogously $E[x_t|x_{t-1} = -1] = -\rho$.

[14] $P_t^a - P_t^b = (\phi + \theta) \cdot 1 - (\phi + \theta) \cdot (-1) = 2(\phi + \theta)$.

[15] The exclusion of overnight returns drastically reduces the number of observations especially for the least liquid Dec07 contract on Nord Pool. Results from including overnight returns are similar.

Table 3:
Estimated half spreads for the four contracts at ECX and Nord Pool

Contract	**ECX**			**Nord Pool**		
	$\hat{s}/2$	Adj. R^2	Obs.	$\hat{s}/2$	Adj. R^2	Obs.
Dec05	0.0624	0.2110	2,256	0.0750	0.1827	501
Dec06	0.0531	0.1743	8,011	0.0877	0.0854	1,266
Dec07	0.0323	0.0587	5,197	0.0487	0.1159	296
Dec08	0.0284	0.1704	23,482	0.0582	0.2487	2,248

This table depicts estimated half spreads $\hat{s}/2 = \hat{\phi} + \hat{\theta}$ in Euro cents for ECX and Nord Pool obtained by GMM estimation of Equation (3) under the given moment conditions. Estimation periods for the Dec05, Dec06, Dec07, Dec08 contracts are 05/01/2005-12/01/2005, 07/01/2005-12/01/2006, 06/01/2005-12/03/2007 and 05/01/2006-12/28/2007, respectively.

It can be seen that for each contract, estimated half-spreads on ECX are lower than on Nord Pool.[16] The graduate decrease in spread magnitude for the different contracts on ECX is consistent with a maturing and expanding market. Interestingly, the pattern is slightly different on Nord Pool. While for the Dec05 contract spreads are of similar magnitudes, the relative distance increases over Phase 1.[17] Additionally, absolute estimated half spreads do not monotonically decrease over the differing contracts on Nord Pool. Hence, estimations indicate that limits to arbitrage induced by transaction costs tend to be lower on ECX than on Nord Pool. Since it seems plausible to detect more frequent price updating on the exchange with lower bid-ask spreads, we expect ECX to be the leader with respect to price discovery, the second part of our study. However, if differences in bid-ask spreads stem from the presence of a higher probability of informed trading on Nord Pool relative to ECX, results might be the other way around.[18]

To improve our understanding about how liquidity (measured by traded bid-ask spreads) has developed over time we subdivide the estimation periods into finer time intervals. Results from separate estimations by year and contract indicate that both on ECX and on Nord Pool, spreads decrease over time. Table 4 shows the development of estimated half spreads in Euro and percent for subsequent calendar quarters. In case that there are less than 150 observations, the preceding month is included into the analysis as indicated at the bottom of the table. If there are still not enough observations, no estimation results are reported.

Interestingly, at the very beginning of trading (Q2 and Q3 of 2005), the relative difference of spreads on Nord Pool and ECX is small. From the fourth quarter (Q4)

[16] As estimates are based on non synchronized data, i.e. on different trading frequencies, it is not possible to directly compare spread magnitudes in a statistical sense. In order to be able to make a statement, we conduct a Wald test of equality of estimated half spreads across exchanges. Explicitly, we test whether the sum of estimated coefficients ($\hat{s}/2 = \hat{\phi} + \hat{\theta}$) of one exchange is equal to the value of the estimated half spread of the other one. We reject the null hypothesis of equality when the Wald test is rejected for both ECX and Nord Pool. Our comparisons of the two platforms are thus all based on the Wald tests.

[17] Note that the Wald tests reject equality at a level of 5% for all contracts except for the Dec05 contract.

[18] Compare also Hasbrouck (1995), p. 1184.

Table 4:
Estimated half spreads for the four contracts at ECX and Nord Pool by calendar quarters

Contract		ECX				Nord Pool			
		$\hat{s}/2$	in %	Adj. R^2	Obs.	$\hat{s}/2$	in %	Adj. R^2	Obs.
Dec05	Q2 2005	0.0614	0.31	0.2889	445	0.0594	0.31	0.2025	206
	Q3 2005	0.0769	0.34	0.2355	1,240	0.0933	0.40	0.1765	270
	Q4 2005	0.0418	0.19	0.1388	709	0.0657	0.29	0.2443	156
Dec06	Q2 2005								
	Q3 2005								
	Q4 2005	0.0655	0.30	0.1295	411				
	Q1 2006	0.0448	0.17	0.2393	2,032	0.0810	0.30	0.2807	223
	Q2 2006	0.0797	0.50	0.2039	2,625	0.1252	0.79	0.0678	503
	Q3 2006	0.0362	0.22	0.2506	1,493	0.0587	0.36	0.2534	286
	Q4 2006	0.0303	0.32	0.1428	1,682	0.0520	0.42	0.1933	232
Dec07	Q2 2005								
	Q3 2005								
	Q4 2005								
	Q1 2006	0.0592	0.21	0.1571	372				
	Q2 2006	0.0695	0.39	0.0476	489				
	Q3 2006	0.0430	0.25	0.2067	455				
	Q4 2006	0.0300	0.35	0.1499	1,441				
	Q1 2007	0.0213	1.02	0.2267	1,636				
	Q2 2007	0.0118	2.19	0.2202	572				
	Q3 2007	0.0059	4.53	0.1807	154				
	Q4 2007								
Dec08	Q2 2005								
	Q3 2005								
	Q4 2005								
	Q1 2006								
	Q2 2006	0.1116	0.52	0.0636	308				
	Q3 2006	0.0499	0.28	0.1658	305				
	Q4 2006	0.0437	0.25	0.1966	1,625				
	Q1 2007	0.0404	0.27	0.2981	3,333	0.0775	0.50	0.3103	263
	Q2 2007	0.0321	0.15	0.2714	4,944	0.0696	0.31	0.2769	722
	Q3 2007	0.0216	0.11	0.2727	7,303	0.0608	0.30	0.2786	507
	Q4 2007	0.0205	0.09	0.2658	5,712	0.0315	0.14	0.1967	724

This table depicts estimated half spreads $\hat{s}/2 = \hat{\phi} + \hat{\theta}$ in Euro cents for ECX and Nord Pool obtained by GMM estimation of Equation (3) under the given moment conditions. Percentage spreads are obtained by dividing the estimated half spread by the median price level of the estimation period. Estimation periods are as indicated with e.g. Q3 2006 denoting July to September 2006. For Nord Pool, the last estimations for the Dec05 and Dec06 contract are from September to December of the respective year. For ECX, estimates for the third quarter 2007 (Q3 2007) are from June to September 2007. Results with less than 150 observations are not depicted.

of 2005 onwards, however, estimated transaction costs on ECX are lower than on Nord Pool.[19] It can be observed that spreads vary over time on both exchanges. The decreasing trend in absolute terms for all contracts is only broken twice. A temporary increase in the third quarter 2005 might be linked to the surge in oil and gas prices related to damages caused by the hurricanes Katrina and Rita in September 2005 and it may be related to the volatility increase in the market in July 2005. The increase in the second quarter

[19]Note that the Wald tests reject equality at the 5% level for all contracts and quarters except for the first two traded quarters (Q2 and Q3) of 2005.

(Q2) 2006, the quarter with the highest absolute and percentage spreads for all contracts traded at that time, can be clearly linked to the market breakdown when the significant over-allocation of EUAs became public at the end of April 2006. Percentage half spreads that are reported in columns 4 and 8 of Table 4 generally move in line with absolute spread magnitudes. Only for the Dec07 contract percentage spreads are increasing while absolute spreads decrease since the market price fell to almost zero. We must acknowledge that our quarterly application meets its limits with respect to Nord Pool. Due to a lack of trading intensity, we must report many blank cells.

Making use of the fact that our model does not only allow us to estimate spread magnitudes, but also to decompose traded spreads into an asymmetric information (θ_t) and a transitory component (ϕ_t), we observe that the asymmetric information component constitutes the vast majority of the traded spread. Taking the more liquid platform ECX as an example, the transitory component comprising order processing costs, mark-ups and inventory costs is at least 20% relative to the permanent component in only 30% of the estimations. For 55% of the estimations, we cannot reject the null hypothesis that the transitory component is different from zero at a level of 10%.[20] Interestingly, the share of the permanent component is lowest in the year 2007 for the Dec07 contract. For all contracts traded, there is a (local) peak in the permanent share in the second quarter of 2006. Hence, it appears that bid-ask spreads charged by liquidity providers in the European CO_2 market are mainly charged as a protection against losses to informed traders (see e.g. Bagehot (1971) or Glosten and Milgrom (1985)) and only to a marginal extent as a compensation for order processing or inventory costs. Given the extensive amount of uncertainty in the market about the development of price drivers as energy and fuel prices or about regulatory issues concerning future National Allocation Plans and the use of project based EUAs (CERs) as well as private news on the installation level, this result does not come as a surprise.

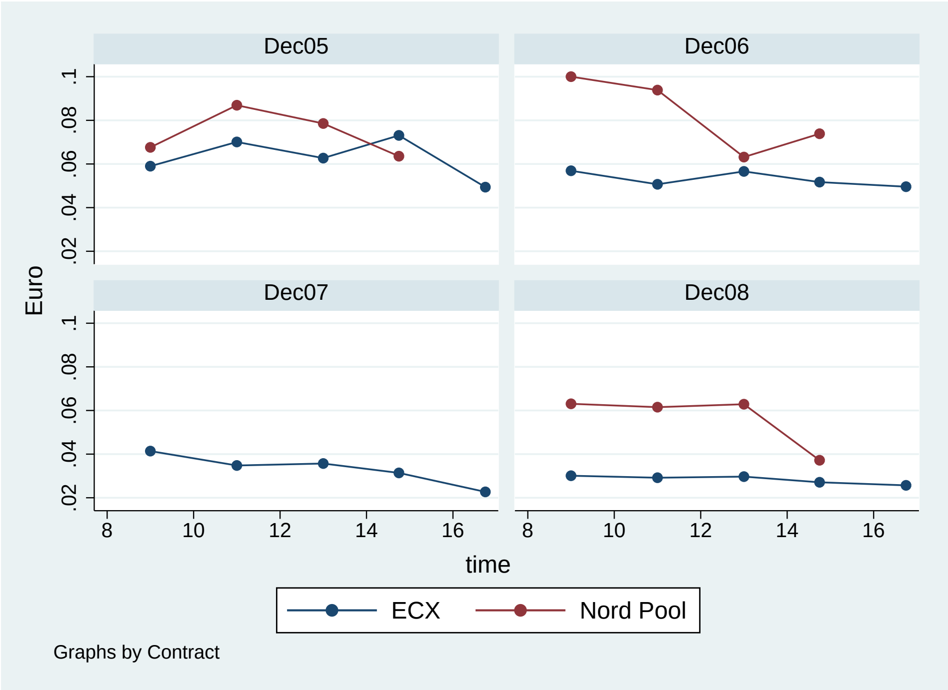
As a last exercise, we assess the intraday pattern of estimated bid-ask spreads. Figure 4 plots intraday half-spreads for both platforms estimated over the full common sample period against trading hours. The intervals of the day that we use for estimations are from 08:00 to 09:59, from 10:00 to 11:59, from 12:00 to 13:59 and from 14:00 to 15:29 for ECX and Nord Pool. Since trading on ECX takes place until 18:00 CET, for ECX the last intraday estimates are from 15:30 to 18:00.[21] If the market processes information or resolves uncertainty during the trading day, we would expect to see spreads decline in the course of trading as observed in other markets.[22] Obviously, this is the case when investigating the patterns in Figure 4. Considering e.g. the Dec06 contract, on average, the trading day at ECX (Nord Pool) starts with an estimated half spread of Euro 0.06

[20]Estimating the model by OLS and accounting for serial correlation by the use of Newey-West errors, significance levels slightly increase.

[21]Note that results are not affected by the choice of time intervals.

[22]See e.g. Madhavan, Richardson, and Roomans (1997) and the discussion in Biais, Glosten, and Spatt (2005)

Figure 4:
Intraday Pattern of estimated half-spreads at ECX and Nord Pool separated by the four contracts



(Euro 0.10) and closes with a half spread of Euro 0.05 (Euro 0.07).

Regarding the share of the permanent spread component relative to the overall spread, we find on ECX that except for the Dec07 contract, asymmetric information costs charged by liquidity providers decline over the course of the trading day.[23] For Nord Pool, however, no clear-cut picture emerges.

If it can be expected that the market development continues and that overall uncertainty decreases in the future, we expect bid-ask spreads to decrease over the next trading phase 2008-2012 to levels close to Euro 0.01. Overall, the development of transaction costs speaks in favor of a maturing market in which traded volumes and trading intensity increase over time while transaction costs fall. Continuing from very low spread levels at the end of 2007, the EU ETS seems to be on a good way with respect to the functioning of organized EUA trading.

4 Price Discovery

In this section we want to determine which exchange is the first to process incoming information into prices. Note that the econometric model that we are going to apply in this section is not related to the bid-ask spread analysis from the previous section. However, the previous results may give some intuition for the expected outcomes with

[23]Results are available from the authors upon request.

respect to price discovery.

Following common practice in the literature on financial and commodity markets, we approach the question of price discovery by specifying a vector error correction model (VECM). We proceed by describing the econometric methodology before applying it to the EUA futures market making use of high frequency data. As detailed above, observing lower transaction costs and higher trading volumes on the platform ECX, our prior is to expect a leading role for ECX. Correspondingly, before specifying an error correction model, we use a conservative matching method that dis-favors ECX, which we labeled earlier as NP-Match, in order to be sure that results are not driven by the use of newer ECX prices compared to Nord Pool.

Generally, the use of high frequency data is only more appropriate compared to daily data if events in the market under examination are also of high frequency. To obtain an intuition on whether this is the case, we compute the fraction of zero returns from one matched transaction in one market to the next one. For the matching approach favoring Nord Pool (NP-match), the fraction of zero returns for Nord Pool ranges from 0.19 to 0.34 for the different contracts. For ECX values are higher and range from 0.38 to 0.45. Compared to more mature markets, these figures are rather high. However, apparently there is more information in intraday data compared to daily data such that there is reason to use data of highest frequency.[24]

4.1 Methodology

Cointegration and Error Correction

Generally, price discovery is the process by which markets attempt to find (discover) equilibrium prices by incorporating new information.[25] In case that an identical asset is traded at the same time in several markets, due to no-arbitrage arguments there should be no significant price differences acoss the markets. Formally, this means that there is an equilibrium price of the asset, which is common to all markets, and the sources of its price variation are attributed to different markets. While market efficiency implies that new information is impounded instantaneously into prices, markets process and interpret news at different rates (e.g. due to institutional factors such as transaction costs) and thus disequilibria occur, especially in an immature market like the EU ETS.

Explicitly, in our case of two markets this means that the two prices may be driven in a fundamental sense by one market, which is the price leader whereas the other market acts as a price taker. The price leader thus incorporates news faster into prices than the other market. Hence, returns on this market should lead the returns on the other market,

[24]Considering e.g. our third matching approach as suggested by Harris, McInish, Shoesmith, and Wood (1995), figures are lower and range from 0.15 to 0.29 for Nord Pool and from 0.10 to 0.18 for ECX. These magnitudes can also be found on more mature financial markets, see e.g. Theissen (2002).

[25]It has been argued that the process of price discovery in security markets is one of the most important products of a security market (cf. Hasbrouck (1995), p. 1175.)

the contribution to the process of price discovery is higher than the one for the price taker.

To investigate leadership in the EUA futures market, we apply two relative measures of price discovery which both use the vector error correction model (VECM) as their basis. Hence we elaborate on the procedure by Engle and Granger (1987) showing that a VECM framework is appropriate for cointegrated time series.[26] The idea behind cointegration is that while two (or more) time series are non-stationary (I(1) processes) they do not drift too far away from each other, such that their difference will be stationary, or in other words, the price series are cointegrated. In that case, a proportion of the deviation from the equilibrium path from one period is corrected in the next period (error correction, EC).[27] Thus formally, returns should be represented by a VECM of the form

$$\Delta p_t = \mu + \sum_{k=1}^{K} \Gamma_k \Delta p_{t-k} + \alpha\beta' p_{t-1} + \epsilon_t \tag{4}$$

where $p_t = (p_t^{ECX}, p_t^{NP})$ are the log futures prices at ECX and Nord Pool, μ and α are (2×1) vectors of parameters, Γ_k are (2×2) matrices of parameters, and K is the lag-length, which will be determined by the Schwarz criterion. ϵ_t is a (2×1) error vector with mean zero and variance-covariance matrix Ω, Δ is the difference operator (e.g. $\Delta p_t = p_t - p_{t-1}$) and β is the (2×1) cointegrating vector, which is in our case equal to (1 -1).[28] In this model, the current returns are then explained by (i) the past returns on both markets (short-run dynamics induced by market imperfections), and (ii) the deviation from the no-arbitrage equilibrium (long-run dynamics between the price series), i.e. $p_t^{ECX} - p_t^{NP}$.[29] Consequently, the cointegrating vector defines the long-run equilibrium, while the EC dynamics characterize the price discovery process. Note that the coefficient vector of the EC term $\delta = (\delta^{ECX}\ \delta^{NP})$ is (by construction) orthogonal to the EC coefficient vector α. This coefficient vector is needed to compute the following two common factor measures for price discovery.

Common Factor Measures

Currently, there exist two popular common factor models that allow to investigate the mechanism of price discovery and that both base on the VECM framework. One has been introduced by Schwarz and Szakmary (1994) and only regards the error correction process, i.e. only δ is relevant. The other measure has been suggested by Hasbrouck (1995)

[26]Note this approach is equivalent to estimating a VAR model of log returns on both exchanges augmented by a so called error correction (EC) term, i.e. a term including the difference between lagged prices on both exchanges.

[27]The relationship between ECM and cointegration was first pointed out in Granger (1981). A theorem showing precisely that cointegrated series can be represented by an ECM was originally stated and proved by Granger (1983).

[28]We did not explicitly estimate but rather pre-specified the cointegration vector since the long-run equilibrium is given by $p_t^{ECX} - p_t^{NP} = 0$, see e.g. Theissen (2002).

[29]Compare also Baillie, Booth, Tse, and Zabotina (2002), p. 311.

and additionally takes into account the variance of the innovations to the common factors of the price series.[30]

Common Factor Weights (CFW)

Schwarz and Szakmary (1994) argue that the coefficients δ^{ECX} and δ^{NP} in the VECM in Equation (4) represent the permanent effect that a shock to one of the variables has on the system. Therefore they propose to use the relative magnitude of these coefficients to assess the contributions of the two trading systems to price discovery. Specifically, they propose the measure

$$CFW^{ECX} = \frac{\delta^{NP}}{\delta^{NP} - \delta^{ECX}}; \quad CFW^{NP} = \frac{-\delta^{ECX}}{\delta^{NP} - \delta^{ECX}}. \tag{5}$$

A high magnitude of δ_i (i = ECX, NP) in the respective market corresponds to slow information dissemination. Apart from describing adjustment dynamics, the coefficients measure the speed of assimilation to discrepancies between the markets. Hence the sum of the coefficients measures the total adjustment to a shock in one or both markets. Thus, the common factor weights quantify the share of total reaction being attributable to one market. Our hypothesis of zero price discovery on Nord Pool then corresponds to the case $CFW^{ECX} = 1$. If Nord Pool also contributes to price discovery, $CFW^{ECX} < 1$.[31]

Information Shares (IS)

The information share approach of Hasbrouck (1995) relates the contribution of an individual market's innovation to the total innovation of the common efficient price instead of only focusing on coefficients of the deviation term. To derive the IS formula, Hasbrouck transforms Equation (4) into a vector moving average (VMA)

$$\Delta p_t = \Psi(L) e_t. \tag{6}$$

Its integrated form can be written as

$$p_t = p_0 + \Psi(1) \sum_{s=1}^{t} e_s + \Psi^*(L) e_t, \tag{7}$$

where p_0 is a vector of constant initial values, $\Psi(L)$ and $\Psi^*(L)$ are matrix polynomials in the lag operator, L, and the (2×2) matrix $\Psi(1)$ is the sum of the moving average

[30] For a comparison of both measures, see the discussion by De Jong (2002); Baillie, Booth, Tse, and Zabotina (2002).

[31] A formal justification can be derived from the work of Gonzalo and Granger (1995).

coefficients. It is called the impact matrix as $\Psi(1)e_t$ (for $s = 1, ..., t$) measures the long-run impact of an innovation on each of the prices. Due to the pre-specified cointegration vector $\beta = (1 \ -1)$ the long-run impact is the same for both prices. This translates into an impact matrix whose rows are identical. With $\psi = (\psi_1 \ \psi_2)$ being the common (1×2) row vector of $\Psi(1)$, Equation (7) becomes

$$p_t = p_0 + \iota(\psi \sum_{s=1}^{t} e_s) + \Psi^*(L)e_t, \tag{8}$$

where $\iota = (11)'$ is a column vector of ones. While $\Psi^*(L)e_t$ simply denotes the transitory portion of the price change, Hasbrouck defines the first part of Equation (8) – the random-walk component – as the common factor component or the common efficient price in the two markets.[32] The common factor innovations (increments) ψe_t (for $s = 1, ..., t$) are the components of the price change that are permanently impounded into the price and that are presumably due to new information. Thus, it is this part we are interested in when analyzing the process of price discovery.

We observe that the innovations' covariance matrix Ω is not diagonal as price innovations are correlated across the two markets. To investigate the proportion of the total variance in the common efficient price that is attributable to innovations in one of the two markets (hence, its information share), the variance of the common factor innovations , i.e. $\mathrm{Var}(\psi e_t) = \psi\Omega\psi'$ has to be decomposed. The Cholesky factorization of $\Omega = MM'$ can be applied to minimize contemporaneous correlation, where M is a lower triangular (2×2) matrix.[33] The information shares are given as follows:

$$S_j = \frac{([\psi M]_j)^2}{\psi\Omega\psi'}. \tag{9}$$

There are many different factorization of Ω. Due to the nature of the Cholesky decomposition, the lower triangular factorization maximizes the information share of the first market and, consequently, minimizes the share of the second market. Thus, by permuting ψ and Ω, upper and lower bounds for each market's information share are obtained. Following the literature, we use the mean of the upper and the lower bound as a unique measure of a market's information share. As formally justified by e.g. Martens (1998) and Theissen (2002), the common row vector ψ is directly related to the coefficient vector of the EC term δ, i.e. $\frac{\psi_1}{\psi_2} = \frac{\delta_1}{\delta_2}$. Together with Equation (9) and by noting that

[32] His specification is closely related to the common trend representation of prices from different markets in Stock and Watson (1988)

[33] Hasbrouck (1995) states that most of the contemporaneous correlation comes from time aggregation as in practice, market prices usually change sequentially. As one way to minimize the correlation, he suggests to shorten the interval of observation and to synchronize the data. However, as this will only lessen but not eliminate the contemporaneous correlation, he additionally proposes the triangularization of the covariance matrix.

$S_{ECX} + S_{NP} = 1$ the IS can be then rewritten as

$$S_1 = \frac{(\delta_1 m_{11} + \delta_2 m_{21})^2}{(\delta_1 m_{11} + \delta_2 m_{21})^2 + (\delta_2 m_{22}^2)} \quad (10)$$

$$S_2 = \frac{(\delta_2 m_{22})^2}{(\delta_1 m_{11} + \delta_2 m_{21})^2 + (\delta_2 m_{22}^2)} \quad (11)$$

Both equations show that the IS only depend on the vector α (or its orthogonal vector δ) and Ω.[34] They also show that the factorization imposes a greater IS on the price of the first market (unless $m_{21} = 0$ i.e., no correlation between market innovations exists).

4.2 Estimation Results

After applying stationarity and cointegration tests to our price series, we present the estimation results of price discovery in three steps. The first part describes the results of the VECM estimations, the second part the information shares and the common factor weights. Note that we applied the methodology to each data synchronization scheme. As the NP-Match is of highest interest for our study, we explicitly report its estimation results and only verbally describe deviations from the other two matches.

Stationarity and Cointegration Tests

Proper interpretation of cointegration models requires that all futures prices contain a single unit root implying non-stationarity (and are thus I(1)). To test for stationarity we apply the well-known Augmented Dickey-Fuller (ADF) unit root test. In this case a significant test statistic means rejection of a unit root in p_t^{ECX} or p_t^{NP}, respectively. Unit root tests have been criticized on the grounds that a failure to reject the null of a unit root does not conclusively show that a unit root exists. It is well known that these tests have low power to distinguish between a unit root and weakly-stationary alternatives (e.g. compare Schwarz and Szakmary (1994)). Consequently, we also implement the Kwiatkowski, Phillips, Schmidt, and Shin (KPSS) stationarity test. In contrast to the ADF or the Phillips-Perron test[35], this test assumes a stationary time series under the null hypothesis. A significant test statistic thus indicates a unit root. For both tests the truncation parameter to select the autocorrelation lag length is chosen according to the Schwarz information criterion.[36]

Table 5 presents the results of the unit root tests for the whole sample period for the

[34] Note that we use a different matrix indexing than Baillie, Booth, Tse, and Zabotina (2002). With m_{21} we denote the entry of the second line in the first column of the matrix M.

[35] As for the ADF test, the null hypothesis for this test is the existence of a unit root.

[36] For a description of the ADF, and KPSS tests, see Dickey and Fuller (1979), and Kwiatkowski, Phillips, Schmidt, and Shin (1992).

Table 5:
Stationarity tests for the four price series at ECX (*upper panel*) and Nord Pool (*lower panel*)

ECX	**level**		**first difference**	
	ADF	KPSS	ADF	KPSS
log(Dec05)	-2.058	0.632**	-25.371***	0.365*
log(Dec06)	-2.444	0.269	-35.306***	0.068
log(Dec07)	-1.624	0.318*	-22.028***	0.076
log(Dec08)	-3.340***	3.67***	-66.800***	0.224

NP	**level**		**first difference**	
	ADF	KPSS	ADF	KPSS
log(Dec05)	-2.013	0.648**	-25.403***	0.299
log(Dec06)	-2.567	0.269	-36.878***	0.068
log(Dec07)	-1.613	0.339*	-21.718***	0.068
log(Dec08)	-3.536***	3.690***	-69.522***	0.225

The table presents the test statistics from Augmented Dickey Fuller (ADF) tests and Kwiatkowski-Phillips-Schmidt-Shin tests (KPSS) applied to both price levels and the first differences of the time series. *,**, and *** denote statistical rejection at the 10, 5, and 1 percent levels, respectively.

NP-Match (April 2005 to December 2007).[37] For the Dec05 and Dec08 contract we do not explicitly consider a trend in the unit root test as a visual inspection of the data fails to provide an indication of a trend (see e.g. Uhrig-Homburg and Wagner (2007)).

With respect to the log price series, ADF tests reject the null hypothesis of a unit root only for the Dec08 contract. The KPSS tests reject the assumption of stationarity for all contracts except for Dec06. We conclude that the evidence is in favor of non-stationarity as indicated by the mostly insignificant ADF and significant KPSS tests, respectively. For the first-differenced series both tests are almost completely in favor of stationarity, only at ECX stationarity is rejected at the 10% level for the Dec05 contract.

Note that applying the unit root tests to the ECX-Match we get the same picture as for the NP-Match. For the Harris-Match, the tests are clearly in favor of non-stationarity of the log prices and of stationarity for the first differences.

Testing for cointegration, we use the likelihood ratio test procedure proposed by Johansen (1988, 1991). The results indicate that the time series from Nord Pool and ECX are cointegrated.

Error Correction Model

We apply the VECM derived above to the synchronized high frequency EUA futures log price series. The VECM in Equation (4) can be written as

[37] Note that futures trading at Nord Pool started in February 2005, while ECX trading was launched in April 2005.

$$\Delta p_t^{ECX} = \alpha^{ECX} + \sum_{k=1}^{K} \gamma_{11,k} \Delta p_{t-k}^{ECX} + \sum_{k=1}^{K} \gamma_{12,k} \Delta p_{t-k}^{NP} + \delta^{ECX}(p_{t-1}^{ECX} - p_{t-1}^{NP}) + \epsilon_t^{ECX} \quad (12)$$

$$\Delta p_t^{NP} = \alpha^{NP} + \sum_{k}^{K} \gamma_{21,k} \Delta p_{t-k}^{ECX} + \sum_{k}^{K} \gamma_{22,k} \Delta p_{t-k}^{NP} + \delta^{NP}(p_{t-1}^{ECX} - p_{t-1}^{NP}) + \epsilon_t^{NP}.$$

The coefficients δ^{ECX} and δ^{NP} determine the speed of adjustment of the respective price towards the long-run equilibrium levels, which is assured by the no-arbitrage argument. If ECX incorporates information faster, we expect δ^{ECX} to be insignificant, while δ^{NP} should be significant and bear a positive sign. The order K of the VECM is determined by the Schwarz information criterion.

Tables 6 and 7 and present estimated common factor measures of the VECM estimation of the NP-Match for all four futures contracts. The first table covers the whole sample period[38] of each contract, whereas the second table takes a closer look at the most liquid trading year of each contract (Dec05: 2005, Dec06: 2006, Dec08: 2007).[39] In order to account for structural breaks the year is divided into three-month intervals such that we can compare the price discovery per calendar quarter across the contracts.[40] To conserve space, we do not display the coefficients on the EC term, ($\delta^{ECX}, \delta^{NP}$) and on the VAR terms, and only report the CFWs for both markets. The coefficients' level of significance is marked by '++' or '+', which indicates that they are significantly different from 0 at the 5% or 10% level, respectively. Furthermore, the tables include the mean information shares for ECX of the upper and lower bound and the corresponding range (difference between upper and lower bound), both are obtained from changing the the ordering in the Cholesky factorization.

For the Dec05 contract we include 2 lags, and for Dec06/ Dec07/ Dec08 we take 8/ 1/ 3 lags, respectively.[41]

We find that for all contracts in both equations of (12) the coefficient of the EC term has the expected sign and is significant at least in one of the markets. Thus, price discovery takes place. Apparently, for Dec05 and Dec06 both markets contribute to the process of price discovery. However, ECX is the clear price leader for the Dec07 and Dec08 contracts. Measuring the markets' contribution to price discovery, both measures tend in the same direction. We find that for later expiration date, prices discovery increasingly takes place at ECX. These results are in line with the development of the EUA futures

[38] As for Dec08 trading activity was very low in 2006, we start the analysis in January 2007.

[39] Due to a lack of observations, we remove the Dec07 contract from the quarterly analysis.

[40] In case that there are less than 190 observations, the preceding month is included into the analysis as indicated at the bottom of the table.

[41] We applied the Schwarz information criterion for the whole sample period as well as for the three-month intervals of each contract. As final lag-length we took the maximum.

Table 6:
Estimation results of the error correction model for all four contracts at ECX and Nord Pool for Phase 1

Contract	EC		CFW		IS for ECX		Obs.
	δ^{ECX}	δ^{NP}	ECX	NP	Mean	Range	
Dec05	++	++	0.593	0.407	0.546	0.790	615
Dec06	+	++	0.811	0.189	0.623	0.725	1433
Dec07		++	0.830	0.170	0.714	0.513	413
Dec08		++	0.847	0.153	0.644	0.693	2402

The table presents the CFWs for both markets and for all contracts together with the information shares for ECX. We report the mean of the upper and lower bound and the corresponding range (difference between upper and lower bound). A '++' or '+' indicates that the coefficients of the error correction vector ($\hat{\delta}^{ECX}\hat{\delta}^{NP}$) are significantly different from 0 at the 5% or 10% level, respectively. For the Dec08 contract, we only use transaction prices from the year 2007.

market. As stated in the introduction, Nord Pool was the first platform which started to trade EUA futures and is thus expected to be the more experienced market for the first months of trading. ECX joined some time later and managed to attract more liquidity in the course of the time.

To counteract critique of analyzing a too long data sample, we zoom into the most liquid trading phase of each contract and divide it into calendar quarters. Note that due to the lack of observations we start the analysis for the Dec05 contract with the second quarter. The results in Table 7 reveal the following interesting pattern for price discovery: Both measures indicate that ECX's contribution peaks in the second (Q2) and third quarter (Q3) compared to the first (Q1) and last (Q4) quarter. An exception constitutes the Dec05 contract, where in the second quarter price discovery still takes place on both platforms. To find possible explanations for this behavior, we analyze quarterly trading activity measured by the average number of daily transaction frequencies and average daily trading volume. Apparently, Table 7 states that the observed price discovery pattern is mostly in line with the one for trading activity: whenever liquidity is increasing ECX mostly leads the price whereas Nord Pool's contribution becomes again observable in calmer times. Noticeable is the sharp decrease in liquidity after the second quarter for the Dec06 contract, which cannot be observed for the other two contracts. As was stated, this behavior reflects the announcement of an considerable over allocation of EUAs at the end of April, which led to a substantial drop in demand for EUAs and thus to a drop in spot and futures prices. Furthermore, it might be the case that findings for the last quarter are related to an earlier expiry of Nord Pool contracts compared to ECX futures.

When interpreting our results it should be kept in mind that the construction of our dataset, NP-Match, puts ECX at a disadvantage and is thus favors the less liquid market Nord Pool. Hence our results are likely to even understate the role of ECX in the process of prices discovery. To check the robustness of our results we estimate the VECM of Equation (12) also for the ECX- and Harris-Match. While results from both matches are even more in favor of ECX they also show that Nord Pool significantly contributes to

Table 7:
Estimation results of error correction model for a restricted sample period together with daily transaction frequencies (TAs) and trading volume

Contract		EC		CFW		IS for ECX		TAs		Volume		Obs.
		δ^{ECX}	δ^{NP}	ECX	NP	Mean	Range	ECX	NP	ECX	NP	
Dec05	Q2 2005	+	+	0.513	0.487	0.513	0.824	11	4	79.8	34.5	179
	Q3		++	0.611	0.389	0.563	0.744	23	5	171.7	42.4	326
	Q4	++		0.133	0.867	0.452	0.897	17	3	141.4	25.8	199
Dec06	Q1 2006			0.565	0.435	0.508	0.940	41	5	415.2	26.2	269
	Q2		++	0.785	0.215	0.624	0.706	57	9	517.2	68.3	540
	Q3		++	0.794	0.206	0.626	0.712	30	6	248.3	41.3	340
	Q4		+	0.688	0.312	0.547	0.866	47	5	313.0	34.0	278
Dec08	Q1 2007			0.367	0.633	0.485	0.932	77	6	675.2	38.1	307
	Q2		++	0.920	0.080	0.765	0.461	145	13	966.7	78.5	775
	Q3		++	0.929	0.071	0.734	0.526	178	10	1296.7	71.3	556
	Q4	+	++	0.683	0.317	0.555	0.831	177	13	1087.4	98.1	764

The table presents the CFWs for both markets and for all contracts together with the information shares for ECX. We report the mean of the upper and lower bound and the corresponding range (difference between upper and lower bound). A '++' or '+' indicates that the coefficients on the error correction vector ($\hat{\delta}^{ECX}\hat{\delta}^{NP}$) are significantly different from 0 at the 5% or 10% level, respectively. In Q4 for the Dec05 and Dec06 contracts the September is included as there are less than 150 observations.

price discovery in the first and last quarters of the most active trading year. We hence conclude that while ECX is the clear price leader in the EUA futures market, our null hypothesis of no contribution to PD by Nord Pool has to be rejected.

As emphasized by Hasbrouck (1995) both common factor measures are based on the common permanent component of prices on both market platforms. That proportion of a market's innovation that helps forecast only transient price disturbances is not considered. They are relative measures that allocate information to the different markets. Furthermore, the implicit efficient price is a statistical construct based on a small subset of market information. There is hence no presumption that the implicit efficient price would fully reflect the information in recent financial statements or upcoming corporate news. Thus, nothing in this approach measures in any absolute sense the total information content of prices. Consequently, to assess the question of price efficiency other analysis tools are needed.

5 Conclusion

In our paper we analyzed high frequency data for European Union Emissions Allowance (EUA) futures for the whole first Kyoto commitment period. Data has been provided by the two most liquid trading platforms ECX and Nord Pool. After having given a short market overview we addressed the issue of market liquidity. We conducted a spread analysis by applying a trade-indicator model. Having two cointegrated price series we were able to measure the process of price discovery by estimating a vector error correction model.

Our results revealed that estimated transaction spreads markedly decreased on both exchanges over time and were lower on ECX than on Nord Pool. With respect to price discovery, our paper demonstrated that for the first EUA futures contracts, Dec05 and Dec06, both exchanges contributed to price discovery. However, for the most recent futures contracts, Dec07 and Dec08, the more liquid market ECX became the price leader, especially in phases of high market liquidity but Nord Pool's contribution was still present from time to time. An intuition for these results may be the fact that an informed market participant has higher incentives to trade on her information in a market with low spreads. If spreads are high, transaction costs may outweigh informational advantages and prices may reflect available information to a lesser extent compared to a market with low transaction costs.

Obviously, our results are not only of academic interest. They indirectly give several market recommendations. First and most obviously, in order to remain (as second competitive platform) in the market and not to lose further market share to ECX, Nord Pool should take some action to attract liquidity. The same is true for other existing market competitors, especially given the large (but decreasing) extent of competition from the OTC market. Besides, the sharp increase in trading volumes over time in this still very young market reveals that there may be a lot of profits for other trading platforms and market participants from entering the (futures) market.

The development potential of the EUA market is extremely high since the EUA can be considered as an European and – depending on future regulatory decisions with respect to additional member states – as a global asset. Low correlations with other financial assets and commodities together with an increasing range of derivative products have furthermore increased the attractiveness of EUAs as an asset class. Hence we would expect to see rapidly increasing interest from the banking as well as the mutual and hedge fund industries in the market such that in the future, compliance trading may no longer constitute the largest share of EUA trading.

Summing up, together with a rapid expansion of the market for EUAs and CERs, in the near future we expect to observe an increasing number of platforms that try to participate in the growing and promising market before seeing a phase of consolidation after which some main trading platforms will emerge.

Recent developments in the carbon market support these statements. In December 2007 Nord Pool has announced to merge with the Nordic exchange OMX to attract further liquidity. Besides, EEX started a cooperation with EUREX in order to increase their market share in EUA futures trading for the Phase 2 and beyond. Not only already established platforms aimed to expand, also new market platforms decided to join the market. In spring 2008 the US American Green Exchange, a cooperation of NYMEX and the environmental broker EvolutionMarkets, launched EUA and CER futures contracts for the years 2008 to 2012. BlueNext, a cooperation between NYSE Euronext and Caisse des Depots was formed in December 2007. It only specializes in carbon related products that have been acquired from Powernext.

Thus, carbon indeed becomes an internationally traded commodity and there is awareness of this steadily growing market. Consequently, the importance of a well functioning market and the guarantee of smooth trading systems are essential. The instruments we are using in our analysis give evidence that after having some difficulties at the beginning, the carbon market is now able to fulfill these requirements. It is possible to track the process of price discovery with the development of the market and to identify the market platform, which is informationally dominant. Besides, bid-ask spreads can be used as a benchmark for liquidity. As our study is the first that includes the additional trading year 2007 in which liquidity has increased significantly and that provides intraday transaction prices, we have the advantage to obtain a more detailed insight into trading patterns compared to prior studies, which we can use and to investigate efficiency measures.

We conclude that as the design for EUA market platforms seems to work and as at least some form of "operational efficiency" has been achieved in the market, the regulatory authorities can concentrate more on issues like the initial allocation process for the EU ETS that have not yet been solved for the upcoming post Kyoto trading period.

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