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ABSTRACT

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How integrated is the European carbon derivatives market?

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June 17, 2015

Abstract

We assess the integration dynamics on the European carbon futures market at both the intraday and daily levels. We focus on EUA futures contracts that can be traded on three trading platforms: the Intercontinental-European Climate Exchange (ICE-ECX), the NASDAQ OMX and the European Energy Exchange (EEX). We analyze trading activity for three contract maturities and find that the ECX and EEX platforms exhibit a reasonable level of integration. The price discovery process does not occur at the daily level but rather at the hourly frequency. We conclude that this market still needs to be closely monitored by the regulatory authorities.

JEL Classification: G13, G14, E44

Keywords: Carbon, derivatives, EU ETS, cointegration, volatility, futures

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1 Introduction

After the ratification of the Kyoto protocol, European governments introduced in 2005 the European Emission Trading Scheme (EU ETS) in spite of substantial political and ideological conflicts. Some governments were indeed reluctant to make concessions, fearing that their leading industries could be deeply impacted by a change in the regulatory framework. By creating such a scheme, the European Union can today be considered as a worldwide pioneer in environmental finance.[1]

The goal of the EU ETS is to limit the emissions of greenhouse gases (GHGs) by setting a ceiling on gas emissions for energy-intensive industries. The main gases covered by the reduction policy include carbon dioxide (CO2), nitric components (NO2), and perfluorocarbon (CnF2n+2). In order to reach that objective, the EU ETS has been divided into several phases. The first four phases are: 2005-2007 (phase I), 2008-2012 (phase II), 2013-2020 (phase III), and 2021-2028 (phase IV). The rules have been changing from phase to phase. For instance, during phase I and phase II, each country subject to the EU ETS needed to implement a National Allocation Plan (NAP) based on its sectorial capacity to pollute. Governments assessed the amount of CO2 emitted by companies based on their respective country. Then, they created their own industry-specific benchmark, that is, the so-called NAP. The European Commission acted as a regulator and approved each NAP. At the starting of phase III, a EU-wide cap has been established for all the countries of the EU ETS, which made national level plans obsolete. This EU-wide cap is reduced by 1.74% each year in order to slowly move to renewable energy.

From a microeconomic perspective, each company has emission quotas to reach and, at the end of the year, they must cancel out the total amount of allowances equivalent to their emitted GHGs in tons all along the year. If their GHG emissions exceed the number of allocated allowances, they must purchase allowances in the carbon market. If they do not violate their allocated emission ceiling (because of an investment in cleaner technologies), they are able to sell their surplus credits, knowing that a company can buy allowances from foreign companies which are subject to the same trading scheme. If surplus could not be banked from one year to another in phases I and II, phase III has introduced this possibility which improves flexibility for companies. At the end of each year, if a company is not in possession of enough allowances to cover all its emissions, it is required to pay heavy fines. Phase III has also expand the use of auctions for the allocation of carbon allowances, as opposed to a free

[1]Kossoy and Guigon (2012) estimate the value of the European carbon market to be worth USD 24.4 billion in 2006 and USD 176 billion (EUR 126 billion) in 2011.

allocation mechanism, which was in place since the advent of the European carbon market. The objective is to phase out free allocation in a near future as pollution should be financed by the most polluting entities.

Carbon markets are now much more divided geographically than they used to. Before phase III, trading schemes around the world included the New Zealand Emissions Trading Scheme (NZ ETS), the New South Wales Greenhouse Gas Reduction Scheme (NSW GGAS) in Australia, the Regional Greenhouse Gas Initiative (RGGI) which is a proposal developed by eleven states from eastern USA, the Western Climate Initiative (WCI) which is a bilateral initiative gathering some American and Canadian states from the West, and the trading scheme of California (AB32). After the starting of phase III, the number of international emissions trading schemes has dramatically increased and we now count 17 already in force emissions trading systems: 7 in China, 2 in Japan, 1 in Korea, 1 in Kazakhstan, 1 in New Zealand, 3 in Northern America and 3 in Europe. Beside these operating ETS, there are 15 more emissions trading schemes under development. To date, the world's biggest and leading infrastructure in terms of trading volume is the EU ETS. Not surprisingly, the most traded carbon-related financial assets in the world are the EUAs (European Union Allowances). Bloch (2011) indicates that EUAs represent 70% of the CO2 traded in the world. The EU ETS is now covering almost 45% of the total emissions of the 28 EU countries.

The EU ETS also allows the trading of two other assets related to the flexibility mechanisms and defined under the Kyoto protocol, i.e. the Emission Reduction Units (ERUs) emitted by Joint Implementation projects (JI) and the Certified Emission Reductions (CERs) issued by the Clean Development Mechanism (CDM). These mechanisms intend to lower the overall costs of achieving the emission targets. They take into account the fact that it could be cheaper for a company to meet Kyoto protocol's requirements in terms of emission reduction by investing abroad. In particular, these mechanisms value foreign investments for the development of cleaner technologies and enable the companies to repatriate the amount of carbon assets associated with the foreign investments. As a matter of fact, the ultimate goal is to reduce the emission of GHGs at a global level; the location of the GHG emissions does not matter much as long as some "clean initiatives" are taken somewhere in the world. A win-win situation may indeed emerge. On the one hand, the home country (or the investor) can fill in its deficit of emission permits. On the other hand, the host country (or the subsidiary) benefits from the transfer of technologies and foreign investments.

All these assets (EUAs, ERUs and CERs) give the same right to its holder, i.e. the right to emit the equivalent of one metric ton of CO2 in the atmosphere. Assets (such as EUAs) emitted during one phase can be banked in another phase but not borrowed from future phases.

As suggested by Newell et al. (2013), carbon markets have grown at such a fast pace, started in such a complicated financial environment (including the 2008 global financial crisis), and faced such critical issues, that it is indeed legitimate to wonder whether these markets function properly and are ultimately sustainable. Phase I of the EU ETS ended in a fiasco. At the start, market participants were considering the price as a good indicator of allowances scarcity. However, in April 2006, a few days before the publication of an official report by the European Commission, EUA prices plummeted by more than 54% in a couple of days and ended up being worth nearly 0. The main cause of this lethal downturn was the over-allocation of assets assigned by the respective NAPs, which were based on erroneous forecasts rather than real CO2 emission measurements. In phase II, EUA spot price opened at around EUR 23 and ended at around EUR 8. All along this period, carbon prices displayed a gradual decrease due to an oversupply of carbon assets on the one hand, and a lower demand of EUAs on the other. The lower need for carbon permits partly resulted from the 2008 crisis and the weak recovery of industrial companies, which were producing less and so emitting less GHGs in the atmosphere. As in the first two phases, carbon prices have been following a similar path in phase III. In April 2013, the European Commission hesitated to implement a backloading plan in order to bolster the market. As a result, EUA prices, already low, plunged. In July 2013, this backloading plan was voted and carbon prices still remained shaky. In order to deal with excessive price fluctuations, the European Commission has proposed a Market Stability Reserve (MSR) instrument whose objective is to address imbalances in supply and demand in the EU ETS. The European Council has also agreed to tackle the oversupply of carbon allowances. The major change is related to the pre-defined rules and the impossibility for a Member State to adapt them. The measure should improve the resilience of the European carbon market to shocks by adjusting volumes for auctions, rather than focusing on allowances prices. The Market Stability Reserve should be in force in 2019.

In 2008, around 1.6 billion EUA contracts were traded on the Intercontinental-European Climate Exchange (ICE-ECX), which represents 96% of the total number of contracts traded under the EU ETS. The remaining contracts were traded on the other two platforms: around 54 million contracts were traded on the NASDAQ OMX, which is equivalent to 3% of the total volume, and around 25 million contracts on the European Energy Exchange (EEX), amounting to 1% of the total volume (Mansanet-Bataller and Pardo, 2011). In 2013, trading volume rocketed but the market shares remained roughly the same. Such an unbalanced oligopoly structure justifies the studies that have been carried out on this new derivatives market. Policy responses to the following questions may have indeed important social welfare implications: Is this oligopoly functioning properly or is the ECX gaining monopolistic advantages because of a lack of integration? Are these two satellite trading platforms disconnected from the dominant exchange? Would it be preferable to close them down to prevent any further deadweight loss? Our study does not pretend to address all these questions, but we believe it is a first step in the right direction.

The goal of this paper is precisely to assess the integration dynamics on the European carbon futures market at both the intraday and daily levels. We focus on EUA futures contracts that can be traded on the three above-mentioned trading platforms: ECX, OMX and EEX. Even if price formation processes have been vaguely discussed in the existing literature, to the best of our knowledge, no study has ever examined the integration dynamics on these three exchanges using Phase II data.

Several relevant papers have been written on the EU ETS. All of them recognize that the scheme had a tumultuous birth and that lessons can be learned from the difficulties faced in phases I and II. Daskalakis and Markellos (2008) highlight the immaturity of the European carbon market, as well as its weaknesses stemming from the constraints on allowances set by policymakers, most notably on banking and short-selling operations. Bredin and Muckley (2011) investigate whether economic factors, weather conditions as well as energy prices, have an influence on the EU ETS prices. The results point to a turning point at the beginning of Phase II where prices have become more related to fundamentals than in Phase I, as outlined by Chevallier (2009). Bredin and Muckley (2011) further document this relationship, while Chevallier (2011) shows that carbon prices negatively respond to shocks in the fundamentals. Niblock and Harrison (2011) also underline the sensitivity of the carbon market to exogenous events. Carbon prices have indeed been highly volatile due to a succession of exogenous events, such as the 2008 global crisis, the European sovereign-debt crisis, the failure of the Copenhagen Summit in 2009, and the shutdown of nuclear power stations in both Japan (following the 2011 earthquake) and Germany (due to political and public worries about nuclear safeness).[2] Benz and Truck (2009) also suggest the existence of more than one regime for price fluctuations, consistent with Bredin and Muckley (2011), and advocate for the use of Markov switching regimes as well as AR-GARCH specifications for carbon price modelling. Paolella and Taschini (2008) also argue in favor of GARCH models but rather emphasize the quality of mixed-normal

[2]Electricity and carbon prices are highly correlated. See Keppler and Mansanet-Bataller (2010).

GARCH models for carbon and environment-related derivatives. Rotfuß (2009) assigns a traditional volatility U-shape to intraday carbon price patterns and a long-memory property to daily European allowances volatility while Rittler (2012) addresses the volatility transmission from the futures market to the spot market and concludes that the futures market leads price discovery. Conrad et al. (2012) further investigate volatility at the intraday frequency and find that the best model to capture these dynamics is a fractionally integrated asymmetric power GARCH process. They further suggest that some events, including political decisions from the European Commission regarding carbon markets, have a strong influence on the price of carbon allowances. Although the initial idea was to create a market promoting sustainable growth and low investment risk, the carbon market has instead turned into a highly speculative and risky place. According to Niblock and Harrison (2011), the stability and sustainability of the EU ETS is even at stake if these trends continue. Kossoy and Guigon (2012) however note that "the collective demand for carbon permits and offsets has a limited impact in market players' trading. A considerable portion of the trades is primarily motivated by hedging, portfolio adjustments, profit taking, and arbitrage."

Regarding our study, the most insightful paper is Mizrach (2012) who looks at the integration of the global carbon market. His paper suggests that the spot market is fully cointegrated in the EU ETS and the EUA futures are also cointegrated in both phases. He further outlines a Granger causality between European and US markets. Even if this study focuses on the first two phases, his sample ends in April 2010. Our study complements the latter one by investigating the total European carbon market both at the daily and intradaily levels, using transaction prices and midquote prices. Benz and Hengelbrock (2008) also look at two exchanges, use intraday prices over the 2005-2007 period, and employ the Engle-granger methodology. Consistent with this research, Mizrach and Otsubo (2014) investigates the microstructure of the ECX futures market and provide evidence suggesting that it drives a major part of price discovery. They also find that the order book is informative and that a simple trading strategy based on order imbalances can lead to profitable returns, even after the inclusion of the main implicit cost components. In addition to these two papers, Medina et al. (2014) also indicate that both market liquidity and trading activity have been improving from Phase I to Phase II, making the carbon market more mature. In our paper, we look at three exchanges representing the total European carbon market volume, use both daily prices (2010-2013) and intraday quotes (2012-2013), and apply the superior cointegrated model by Johansen.[3] To the

[3]In the Engle-Granger methodology, the cointegrated model is reduced to a single equation and there is no statistical test on the coefficients of the long-term relationship. That is the reason why the Johansen approach is typically preferred.

best of our knowledge, no research study has investigated integration dynamics on the whole market activity on EUA contracts in the second phase both at the daily and intraday levels.

The remainder of the paper is organized as follows. Section 2 is devoted to the statistical methods used in this paper. Section 3 discusses the results. The final section concludes and provides some policy recommendations.

2 Methods

Among the three exchanges that we study, the ICE-ECX is the leading trading platform in terms of trading activity. The NASDAQ OMX and the EEX are two smaller markets, which are on an equal footing with respect to trading volumes. Such a market structure is expected to have an impact on market fundamentals such as the level of volatility and the quality of the price discovery process, as outlined by previous research.

EUA futures can take different maturity dates, the most liquid maturities being December, as also outlined by Mizrach and Otsubo (2014). In the empirical analysis, we focus on the December 2013, 2014 and 2015 futures contracts traded on the three above-mentioned exchanges. Table 1 gives a quick overview of the EUA carbon futures contract traded on the three platforms. The December 2013 maturity is taken as an example. The data used in the empirical analysis were collected on Bloomberg and downloaded under a unique time zone (GMT+1). The trading day on ICE-ECX begins at 7AM until 5PM GMT and is perfectly coordinated with trading hours on both EEX and NASDAQ OMX, going from 8AM and close at 6PM at GMT+1. We exclude overnight intervals, pre-opening or post-closing periods in order to focus on the carbon market when there is continuous trading on all platforms.

We do not use intraday transaction prices because transactions are not filled simultaneously on the three exchanges, as expected. For instance, a high volume can be traded on one platform while no transaction occurs in the other two exchanges. We therefore use daily data on trades because there is no synchronization issue at the daily frequency. There is indeed at least one transaction per day on each platform. For the December 2013 contract, data on transaction prices are available from June 29 2010 to March 11 2013. For the December 2014 contract, the time period ranges from June 29 2010 to April 15 2013. Finally, it goes from June 11 2012 to April 12 2013 for the December 2015 contract.

Figure 1 presents the time series of the transaction prices and the corresponding log returns for the December 2013, 2014, and 2015 futures contracts on the three trading platforms. The first / second / third column refers to the ICE-ECX / NASDAQ OMX / EEX platform, with the corresponding Bloomberg ticker (MOZ / FUAZ / UJLZ, respectively). Table 2 reports the key descriptive statistics on the log returns. In Table 3, we measure the unconditional and GARCH-type volatilities on the three exchanges for the three futures contracts. A quick look at the volatilities confirms that the carbon market is very volatile indeed. GARCH volatilities are higher than unconditional volatilities but there is no systematic difference in volatility between the three exchanges.

By using bid and ask quotes, we are also able to look at the integration dynamics between the three markets at the intraday level. There is indeed no synchronization issue for bid and ask quotes since they are always displayed when the market is open, irrespective of whether there is a transaction on the platform or not. In addition, by using the midquote instead of the transaction price, we avoid the intraday bouncing of trade prices between the bid and ask. We use hourly data on midquotes in the empirical analysis. For the three futures contracts, intraday data on bid and ask quotes are available from August 8 2012 to April 4 2013.

All in all, the two types of data (on daily transaction prices and intraday bid-ask quotes) are complementary. On the one hand, daily data on trades are useful because they represent real transactions between market participants. On the other hand, intraday data on midquotes are useful because it is possible to take a micro perspective on the degree of integration between the markets by avoiding at the same time the "no synchronization" and "bid-ask bounce" issues.

In Table 4, we report the median for three key measures of liquidity: The proportional spread ($PropSpread$), the volume spread ($VolSpread$) and the quote slope ($QuoteSlope$). These variables are computed as follows:

$$PropSpread_t = \frac{ask_t - bid_t}{m_t}, \tag{2.1}$$

$$VolSpread_t = \frac{ask_t - bid_t}{volume_t}, \tag{2.2}$$

$$QuoteSlope_t = \frac{ask_t - bid_t}{ln(q_t^a sk) + ln(q_t^b id)}, \tag{2.3}$$

where m_t is the midquote and is computed as $m_t = (ask_t + bid_t)/2$, and $q_t^a sk$ ($q_t^b id$) is the quantity available at the ask (bid) at time t.

Compared to traditional stock markets, liquidity on the European carbon market is significantly lower, even if it is improving with time. Among the three exchanges, we find that ICE-ECX is the most liquid exchange, irrespective of the liquidity measure considered. We do not observe any significant difference between the NASDAQ OMX and EEX platforms in terms of liquidity. When futures contracts are compared, the December 2013 contract is the most liquid contract on each of the three trading platforms. This is confirmed for each of the three liquidity measures. As for traditional future contracts, the nearest maturity date is most of the time the most liquid one in carbon markets, even if particular attention is paid to December futures, as outlined by Mizrach and Otsubo (2014).

We estimate the integration dynamics of the European carbon futures market by using a Vector Autoregressive Correction Model (VECM). This model allows us to test for cointegration, i.e. to estimate the long run (no-arbitrage) equilibrium between the three futures markets. In our study, we investigate the daily log price dynamics of EUA futures on three different exchanges. We also carry out a similar analysis for intraday bid-ask quotes. In both cases, the number of variables in the VECM is equal to 3 ($g = 3$).

If the carbon market is not dysfunctional, a long-run (i.e. no-arbitrage) equilibrium must be found. We therefore expect to find a statistically significant cointegration vector for both price and quote variations on the three exchanges, with the appropriate coefficient signs. When the market price reflects the long run price equilibrium, mean-reversion dynamics in transaction prices cannot be exploited. In such a case, deviations from the no-arbitrage equilibrium (i.e. long-run disequilibrium effects) and short-run time dependencies in prices (induced by market imperfections) cannot help explain current returns and do not bear on the price discovery process.

In the cointegrated model by Johansen, the general VECM can be written as

$$\Delta p_t = \prod p_{t-k} + \Gamma_1 \Delta p_{t-1} + \Gamma_2 \Delta p_{t-2} + ... + \Gamma_{k-1} \Delta p_{t-(k-1)} + \varepsilon_t, \quad (2.4)$$

where $p_t = (p_t^1 \; p_t^2 \; p_t^3)$, $\prod = (\sum_{j=1}^{k} \beta_i) - I_g$ and $\Gamma_i = ((\sum_{j=1}^{i} \beta_i) - I_g$. The Γ_i coefficients measure the short-run effects as captured by lagged returns. $\prod$ is a long-run coefficient matrix and shows how the prices come to a new long-run equilibrium after a shock. The movement back to equilibrium is the direct result of the prices being cointegrated.

The first step of our cointegration analysis consists in identifying the most appropriate model given the features of the data. There are several candidate models which differ according to the inclusion of a constant and/or a deterministic component (in the model and/or the cointegration vector). In fact, cointegration and price discovery between markets are studied by using a model with no deterministic trend in the cointegrating vector. Adding a deterministic trend is indeed not justified since price series are integrated of order 1; we instead differentiate them to take the stochastic trend into account. The typical model also incorporates an unrestricted constant in the general equation but not in the cointegrating vector (as in deB Harris et al. (1995), Booth et al. (1999)). The unrestricted constant in the general equation may be useful when the average price variations are superior to zero.

The second step requires testing for the cointegration rank (r) of the VAR system to determine whether there are potentially useful cointegrating vectors. This is typically done by running the trace and maximum eigenvalue tests by Johansen (1988) and Johansen (1991) which are robust to non-normal errors and GARCH effects (Cheung and Lai, 1993; Lee and Tse, 1996). The critical values for the Johansen tests are given in Johansen (1991) and Osterwald-Lenum (1992).

The third step involves the determination of the number of lags (k) in the multivariate model. It is determined so that the last included $k+1$ lagged variables in the VAR specification are jointly non-significant. Moreover, we compute the usual univariate and multivariate diagnostic tests and examine the Schwarz Information Criteria (SIC).

If there is one cointegration relationship between the three exchanges with $k = 1$, the VECM can be rewritten as:

$$\begin{aligned}
\Delta p_{1,t} &= \alpha_1 + \delta_1(p_{1,t-1} + \beta_2 p_{2,t-1} + \beta_3 p_{3,t-1}) + \gamma_1 1\Delta p_{1,t-1} + \gamma_1 2\Delta p_{2,t-1} + \gamma_1 3\Delta p_{3,t-1} + \varepsilon_{1,t},\\
\Delta p_{2,t} &= \alpha_2 + \delta_2(p_{1,t-1} + \beta_2 p_{2,t-1} + \beta_3 p_{3,t-1}) + \gamma_2 1\Delta p_{1,t-1} + \gamma_2 2\Delta p_{2,t-1} + \gamma_2 3\Delta p_{3,t-1} + \varepsilon_{2,t},\\
\Delta p_{3,t} &= \alpha_3 + \delta_3(p_{1,t-1} + \beta_2 p_{2,t-1} + \beta_3 p_{3,t-1}) + \gamma_3 1\Delta p_{1,t-1} + \gamma_3 2\Delta p_{2,t-1} + \gamma_3 3\Delta p_{3,t-1} + \varepsilon_{3,t}.
\end{aligned} \tag{2.5}$$

The above VECM relates to the model specification with no trend and an unrestricted constant in the equations. If subscripts 1, 2, and 3 point to the ICE-ECX, NASDAQ OMX, and EEX exchanges respectively, then ICE-ECX is the "benchmark" exchange since $\beta_1 \equiv 1$. When evidence of cointegration is found, we can study the magnitude and statistical significance of the reversion dynamics between the prices (and quotes) on these exchanges.

First, we investigate whether a deviation from the long-run equilibrium between these three exchanges has an impact on prices (and quotes) so that they revert to their long-run equilibrium in a statistical and predictable way, implying that arbitrage opportunities may be possible. This will be indicated by the adjustment speed coefficients (i.e. δ_1, δ_2, δ_3) which determine how each price (or quote) is affected by the disequilibrium in the lagged long-run relationship.

Second, we examine short-term reversion dynamics. Although the disequilibrium in the lagged long-run relationship may not bear on reversion dynamics, it may still be possible to find and exploit short-term price (or quote) time dependence to design arbitrage strategies. This will be indicated by the significance of the gamma coefficients in the VECM.

Third, we test for the presence of indirect effects between the three exchanges, since the relationship between market pairs may not be fully informative. We also use the forecast error variance decomposition (FEVD) technique to further explore the trivariate relationships. FEVD gives the proportion of the movements in the dependent variables that are due to their "own" shocks, versus shocks to the other variables. Finally, we complement the analysis by computing impulse responses (IRs) to one standard deviation Cholesky's innovations. IR functions show the effects of both internal and external shocks on the adjustment path of the dependent variable in each exchange.

3 Results and Discussion

Table 5 clearly indicates that the three exchanges are cointegrated since up to two vectors of cointegration are identified, as indicated by both the trace and maximum eigenvalue tests. In other words, the three exchanges share a long-run price equilibrium and are impacted by one common stochastic factor. The European carbon market is therefore not dysfunctional, at least at first sight and from a statistical point of view. The lag length selection procedure based on the SIC indicates that the optimal number of lags in the VECM is equal to 1 in almost all cases. There is one exception where $k = 3$, for December 2015 contracts when the midquote dynamics are studied.

In Table 6, we use transaction prices and report the estimates for the long-term relationships characterized by the cointegrating vector, including the adjustment speed coefficients. Let us first focus on daily transaction prices (Table 6) and take the case of the December 2013 futures contract. The first two lines correspond to the case where the ICE-ECX exchange is used as the benchmark (as it was assumed in the example above). The first equation in the VECM characterizes the price variations in the ICE-ECX platform. It can be written as:

$$\Delta p_{1,t} = \alpha_1 - 0.025661(p_{1,t-1} - 14.43992p_{2,t-1} + 13.43961p_{3,t-1}) + STdynamics + \varepsilon_{1,t}. \quad (3.1)$$

Under the hypothesis of long-run equilibrium, the equilibrium errors equate to zero. In such a case, $p_1 = p_2 = p_3$ and no arbitrage profit can be made. This arbitrage-free equality of the three prices in synchronous trading is reflected by the finding that literally each of the cointegrating vectors sums to approximately zero. For example,

$$(p_{1,t-1} - 14.43992p_{2,t-1} + 13.43961p_{3,t-1}) \approx 0. \quad (3.2)$$

If there is any disequilibrium, mean-reversion dynamics will play through the adjustment speed coefficient. Its estimate is $\hat{\delta}_1 = -0.025661$. Let us suppose that the futures price on ICE-ECX has recently fallen "too much" with respect to its long-term equilibrium. Then, $(p_{1,t-1}$ is "too low" and the value of the cointegrating vector is negative. Because the adjustment coefficient estimate is also negative (but insignificant), the mean-reversion dynamics will help correct this punctual disequilibrium by pushing $\Delta p_{1,t}$ higher. If the adjustment speed coefficient estimate is close to one (with the sign opposite to the disequilibrium), then it disappears after one day only, ceteris paribus.

In Table 6, we observe that most cointegrating vectors' coefficients are statistically significant at 1%, which corroborates the presence of a long-term relationship between daily log prices on these three exchanges. Consequently, the three markets seem to be informationally connected, with arbitrage being the mechanism by which this connection is realized. The prices of these contracts should therefore not drift apart in the long run on these exchanges. There are nevertheless some variations between exchanges. The "price leading" exchange seems to be ECX since all cointegrating factors are significant when the price deviation from the long-run equilibrium occurs on that platform. It holds irrespective of the contract maturity. On the contrary, a price deviation on the OMX platform does not significantly affect ECX prices for the 2013 and 2014 contracts. It is also the case between the EEX and the ECX, but only for the 2013 maturity. The OMX exchange seems to exhibit some lack of integration with respect to the other two platforms.

Clearly, arbitrage forces are stronger between exchanges when the price deviation comes from the ECX because the cointegrating coefficients on the other two platforms are always statistically significant. On the contrary, the no-arbitrage argument, which leads to long-run equilibrium price levels between these three exchanges, is weakened when the deviation occurs on OMX, suggesting that price deviations may potentially last for a long time in this case. Regarding the adjustment coefficients, we notice that none is statistically significant at 5%, which implies that there is no substantial price adjustment in maintaining the long-run cross-exchange equilibrium from one day to another on these exchanges. When the long-run cross-exchange relationship has been perturbed by the arrival of news the day before, there is no noticeable price effect on the next day closing price on these trading platforms.

Overall, there is very weak evidence that arbitrage profit can be made by attempting to exploit long-term disequilibria in transaction prices on a daily basis between these platforms since no significant price adjustment can be anticipated at the daily level to restore long-run equilibrium. It takes less than a day to incorporate new information and go back to the long-run equilibrium. As indicated in Table 7, there is no price discovery that can be captured at the daily interval when we focus on short-run (cross-exchange) daily effects. No lagged price change displays a significant coefficient estimate. Based on daily log transaction prices, two conclusions can be drawn. First, the price levels on these three platforms are bounded by a long-run no-arbitrage relationship, with OMX being the weakest link. Second, daily changes in log transaction prices on (and between) these exchanges follow a random walk. We conclude that daily transaction prices are close to the long run price equilibrium since no evidence of price discovery is found: Mean-reversion dynamics in transaction prices cannot be exploited.

Results for hourly mid quotes in Tables 8 and 9 give us additional insight into the dynamics of price discovery on these three exchanges. For the three futures contracts, the cointegrating vector coefficients are all statistically significant, confirming that the prices of these contracts should therefore not drift apart in the long run on these exchanges. Most interestingly, the adjustment speed coefficients are statistically significant in many cases. Contrary to daily log prices, there is evidence of mean-reversion dynamics in hourly log mid quotes, following a deviation from the no-arbitrage equilibrium. Conclusions vary across futures contracts. For the December 2013 contract, our VECM results for hourly mid quotes shows that long-run price discovery occurs on all three markets, with no statistical difference between the three exchanges. Nevertheless, the EEX displays the highest absolute adjustment coefficient values, responding faster to deviations from the no-arbitrage equilibrium.

Regarding the December 2014 contract, when the arrival of news perturbs the cointegrating relationship, the adjustment process required to restore equilibrium is mainly done by the ECX exchange. The absolute values of the adjustment speed coefficients on ECX are much higher, implying that the ECX responds much faster than the other two platforms. There is actually no long-run price discovery on EEX and OMX. Results for the 2014 and 2015 contracts are similar, with the difference that the EEX displays significant adjustment coefficients. They remain lower than those of the ECX.

In Table 9, we display the short-term dynamics of the VECM based on hourly mid quotes and investigate the sensitivity of prices to their lagged values. Short-run price discovery is much more pervasive when hourly mid-quotes are used than daily transaction prices. Short-run price effects seem to decrease with the maturity of the contract and be weakest on the OMX platform.

Although the relationship between market pairs is instructive, indirect effects could exist. For example, the OMX may not influence the ECX directly, but it may influence it indirectly through the EEX. This hypothesis is examined by testing the null that for a given platform, there are no price effects coming from the other two platforms. For example, we can test under the null whether the OMX and EEX platforms do not offer useful information for the pricing of the ECX. If they do, the null is rejected. Useful information is captured by the lagged returns of the OMX and the EEX, but also their error correction terms. Based on the Wald statistics reported in Table 10, the null is rejected, suggesting the likelihood of indirect effects, in all cases, except for the 2014 contract on the OMX platform.

We use the forecast error variance decomposition (FEVD) to further explore the trivariate relationships. FEVD gives the proportion of the movements in the dependent variables that are due to their "own" shocks, versus shocks to the other variables. Thus, Table 11 shows the fraction of the forecast error variance that is attributable to the "own" shocks for horizons ranging from 1 to 20 periods. For example, estimates for the 2013 contract after 20 periods indicate that the common factor explains 83.50%, 64.96%, and 50.88% of ECX's, OMX's, and EEX's fluctuations, respectively. The more the price movement is explained by the "own" shocks, the more "self-sufficient" the exchange is. For the 2013 contract, we can also observe that shocks on the OMX and EEX explain a relatively high percentage of the variation in hourly log mid quotes on the ECX (at 33.73% and 48.04%, respectively). The percentages are much lower in the opposite way (at 16.11% and 0.39%, respectively). The transmission of "cross-exchange" shocks coming from the EEX (or OMX) platform to the ECX market is thus more important than the reverse. In other words, the ECX is better at capturing (and transmitting) more quickly and more extensively "outside" information (proxied by shocks coming from another market). If we focus on the two satellite markets, the "cross-exchange" transmission between them is very limited. Following a shock on the OMX market, the EEX platform can only explain 1.3% of the total error variance observed in the OMX midquotes after 20 periods. In the same vein, following a shock on the EEX market, the OMX platform can only explain 1.08% of the total error variance observed in the EEX midquotes after 20 periods. These results are insensitive to the ordering switch between the second and third places, irrespective of the column in Table 11. We do not show them to avoid redundancy but they are available upon request.

We also report the impulse responses (IRs) to one standard deviation Cholesky's innovations. IR functions show the effects of shocks on the adjustment path of the dependent variable over the next 10 periods. Figure 2 clearly shows that ECX and EEX market quotes react to each other's shocks in a rather similar way. In both cases, the impulse responses are nearly identical and stable after 4 periods. Market quotes on EEX even seem to be slightly more reactive than those on ECX. Regarding the OMX platform, market quotes react more to external innovations than to internal ones (as indicated by the crossed line being below the other two lines, on the middle graph). Also, innovations in the OMX quotes affect the adjustment path of the ECX and EEX quotes to a much lower extent than the reverse (which means that innovations in the ECX and EEX quotes affect the adjustment path of the OMX market quotes to a much higher extent, as shown on the middle graph).

For the December 2013 contract, the ECX trading platform seems to display the most attractive quote dynamics, but the EEX market does not lag much behind, given its smaller market share. Nevertheless, the lower level of interconnectedness displayed by the OMX platform is more worrisome. If we had to rank the three markets in terms of integration dynamics for this contract, it would be ECX, EEX, and then OMX quite behind.

For the 2014 and 2015 contracts, there is almost no noticeable "cross-exchange" effect between exchanges. The proportion of the movements in the dependent variables that are due to their "own" shocks is particularly high on the OMX and EEX. The only significant indirect effect is the shock transmission from ECX to OMX, which reveals a weaker integration at these two maturities.

4 Conclusions and Policy Implications

To study the integration dynamics on the European carbon market, we focus on the analysis of three EUA futures contracts that can be traded on three different trading platforms: The Intercontinental-European Climate Exchange (ICE-ECX), the NASDAQ OMX (formerly Nord Pool) and the European Energy Exchange (EEX). To the best of our knowledge, this study is the first to examine the integration dynamics between these three exchanges using Phase II data, both at the daily and intraday levels. Given the unbalanced oligopoly structure of this market, it is important to provide policymakers and regulators with insightful information that may help them better evaluate the functioning of these new exchanges. This study contributes to this effort.

We use both daily transaction prices and hourly mid quotes because these two types of data are complementary. On the one hand, daily data on trades are useful because they represent real transactions between market participants. On the other hand, intraday data on mid quotes are useful because it is possible to take a micro perspective on the degree of integration between the markets by avoiding at the same time the "no synchronization" and "bid-ask bounce" issues.

First, we estimate liquidity on these three exchanges by computing three measures: The proportional spread, the spread on volume, and the quote slope. The ICE-ECX exchange is the most liquid exchange, irrespective of the liquidity measure considered. We do not observe any significant difference between the NASDAQ OMX and EEX platforms in terms of liquidity. When futures contracts are compared, the December 2013 contract is the most liquid contract on each of the three trading platforms. This is confirmed for each of the three liquidity measures.

Second, we estimate volatility both unconditionally and conditionally. We find that the carbon market is very volatile indeed, with GARCH volatilities being higher than unconditional volatilities. There is also no systematic difference in volatility between the three exchanges

Third, the study of price dynamics at the daily level indicates that the ECX platform seems to drive the integration dynamics between the three exchanges. When there is a shock to the long-run equilibrium coming from the ECX, arbitrage forces are stronger since the ECX is the only platform for which all the cointegrating factors (related to the other two exchanges) are significant, irrespective of the contract maturity. On the contrary, the no-arbitrage argument, which leads to long-run equilibrium price levels between these three exchanges, is weakened when the shock occurs on the OMX, suggesting that price deviations may potentially last for a long time in this case.

We find that there is no substantial price adjustment in maintaining the long-run cross-exchange equilibrium from one day to another on these two exchanges. When the long-run cross-exchange relationship has been perturbed by the arrival of news the day before, there is no noticeable price effect on the next day closing price on these trading platforms. The adjustment dynamics towards a new long-run price equilibrium, i.e. the so-called long-run price discovery, would occur at another frequency. The same conclusion can be drawn by looking at the short-run price dynamics. There is no short-run price discovery. Daily changes in log transaction prices on (and between) these exchanges follow a random walk.

Finally, we obtain additional insight into the dynamics of integration and price discovery on these three exchanges by looking at hourly mid quotes. We note that the integration level is stronger at this higher frequency. For each of the three futures contracts, the cointegrating vector coefficients are always statistically significant. Contrary to daily log prices, there is evidence of mean-reversion dynamics in hourly log mid quotes when a deviation from the no-arbitrage equilibrium occurs. When the arrival of news perturbs the long-run cross-exchange relationship, the adjustment process required to restore equilibrium is done by the ECX exchange but the EEX exchange also plays an important role. The absolute values of the adjustment speed coefficients are overall relatively high, implying a rather fast response to any long run disequilibrium. Short-run price discovery is also much more pervasive when hourly mid-quotes are used instead of daily transaction prices. Variance decompositions show that the ECX exchange is the most "self-sufficient" exchange. The ECX is also better at capturing (and transmitting) more quickly and more extensively "outside" information (proxied by shocks coming from another market). If we focus on the two satellite markets, the "cross-exchange" transmission between them is very limited. Through the use of impulse responses, we also show that innovations in the OMX quotes affect the adjustment path of the ECX and EEX quotes to a much lower extent than the reverse. If we had to rank the three markets in terms of integration dynamics for the 2013 contract, it would ECX, EEX, and then OMX quite behind. Overall, we also reveal a lower level of interconnection between the three platforms at the 2014 and 2015 contracts.

In conclusion, we find that the European carbon derivatives market exhibits a reasonable level of integration between the ECX and EEX platforms at the shorter maturities, with the price discovery process occurring at the hourly frequency. This market still needs to be closely monitored by the regulatory authorities given the high level of volatility, the fragile level of liquidity, the relatively weak interconnectedness of the OMX exchange, and the lower level of interconnection at longer maturities.

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Table 1: The December 2013 EUA carbon futures contract

Commodity	EUA (European Allowances) future contract		
Value	1 EUA=1tCO2		
Description	1 lot of 1000 CO2 EUA provides the rights to its holder to emit an equivalent volume of gas		
Lot size	1000 tCO2		
Minimum trading size	1 lot		
Min tick size	EUR 0.01 per lot/No limit		
Min price fluctuation	EUR 0.01		
Maturation date	Dec-13		
Daily settlement price	Established after the end of trading on every exchange trading day		
Margin	Initial and variation margin are charged in the usual manner by each platforms' own clearing house		
Platform	ICE-ECX	EEX	NASDAQ OMX
Location	London, UK	Leipzig, Germany	Oslo, Norway
Time zone	GMT	GMT+1	GMT+1
Trading hours	07:00-17:00	08:00-18:00	08:00-18:00
Bloomberg ticker code	MOZ3 Comdty	UJLZ3 Comdty	FUAZ3 Comdty
First trade	7-Apr-08	30-Jun-10	29-Nov-10
Last trade (expiration day)	16-Dec-13	16-Dec-13	15-Dec-13
Annual fees	EUR 11.50	EUR 10.00	EUR 1.50
Trading fees (EUR/tCO2)	0.002	0.0018	0.003
Clearing fees (EUR/tCO2)	0.015	0.001	0.003
Counterparty risk	Guaranteed by ICE Clear Europe	Guaranteed by ECC	Guaranteed by NASDAQ OMX
Admitted Market makers	Five Rings Capital	RWE Supply & Trading	Alfa Craft AB
VAT and taxes	UK's HM Revenue and Customs has confirmed that the trading of the EUA Futures Contract on the Exchange between the Member and ICE Clear Europe Limited has been granted interim approval to be zero-rated for VAT purposes under the terms of the Terminal Markets Order.	All Cash Settlement Amounts shall be exclusive of VAT with the exemption that the Clearinghouse will charge VAT if this is required under applicable law.	All Cash Settlement Amounts shall be exclusive of VAT with the exemption that the Clearinghouse will charge VAT if this is required under applicable law.
Order type	Pure Limit Order Driven Market for ordinary trades. Limit orders (default) are stored in an open LOB following strict price-time priority criteria, market and block orders		
Trading Model	Continuous trading throughout trading hours. Limit orders can be modified (price/volume) or withdrawn. By default, standing limit orders expire at the end of a trading day.		

Table 2: Log returns for the three futures contracts on the three platforms - Descriptive statistics

	Dec-13			Dec-14			Dec-15		
	ECX	OMX	EEX	ECX	OMX	EEX	ECX	OMX	EEX
Mean	-0.0008	-0.0006	-0.0008	-0.0008	-0.0009	-0.0008	-0.0009	-0.0009	-0.0009
Median	-0.0005	0.0002	0.0000	-0.0005	0.0000	0.0000	0.0000	-0.0005	0.0000
Higher	0.1035	0.0933	0.1019	0.1005	0.0933	0.0971	0.0992	0.0958	0.0971
Lower	-0.0689	-0.0717	-0.0671	-0.0683	-0.0717	-0.0666	-0.0662	-0.0677	-0.0654
Stand. dev.	0.0183	0.0186	0.0182	0.0181	0.0184	0.0180	0.0179	0.0193	0.0178
Skewness	0.5350	0.2346	0.5600	0.4816	0.2179	0.4699	0.4780	0.4139	0.5209
Kurtosis	4.9663	3.7402	4.8634	4.6981	3.8906	4.3567	4.6235	3.6459	4.5827

Table 3: Unconditional and GARCH-type volatilities for the three futures contracts on the three platforms

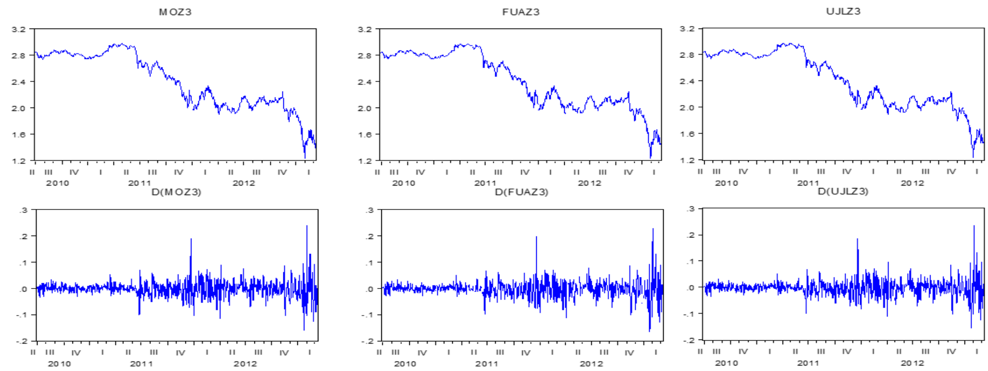
Transaction		ECX		OMX		EEX	
prices		Daily	Volatility	Daily	Volatility	Daily	Volatility
Dec-13	Stand. Dev. (unconditional)	1.83%	29.06%	1.85%	29.30%	1.81%	28.81%
	Stand. Dev. (GARCH)	1.94%	30.76%	1.87%	29.61%	2.03%	32.23%
Dec-14	Stand. Dev. (unconditional)	1.81%	28.79%	1.84%	29.18%	1.80%	28.54%
	Stand. Dev. (GARCH)	1.91%	30.36%	2.30%	36.52%	1.95%	30.92%
Dec-15	Stand. Dev. (unconditional)	1.79%	28.49%	1.92%	30.55%	1.77%	28.13%
	Stand. Dev. (GARCH)	1.92%	30.41%	2.30%	36.47%	1.97%	31.30%

Volatility is presented on an annual basis.

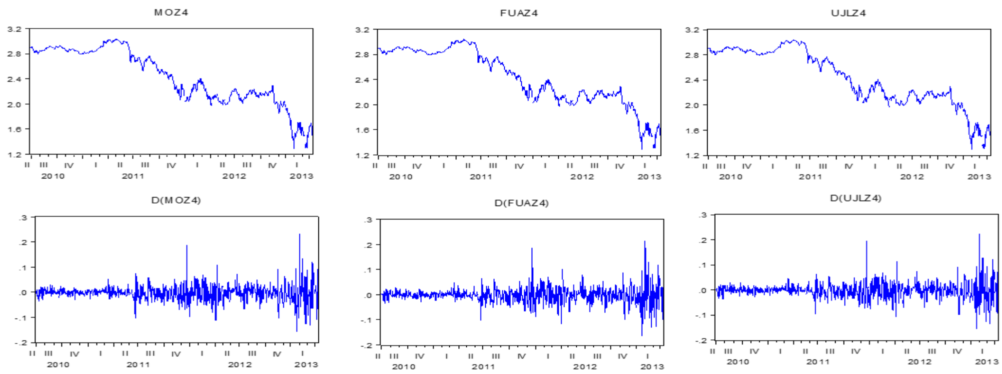
Table 4: Liquidity of the three futures contracts on the three platforms

	Proportional spread			Spread on volume			Quote slope		
Dec-13	ECX	OMX	EEX	ECX	OMX	EEX	ECX	OMX	EEX
Median	0.0042	0.0085	0.0083	0.0000	0.0087	0.0088	0.0020	0.0046	0.0032
Dec-14	ECX	OMX	EEX	ECX	OMX	EEX	ECX	OMX	EEX
Median	0.0058	0.0081	0.0098	0.0005	0.0305	0.0190	0.0027	0.0048	0.0043
Dec-15	ECX	OMX	EEX	ECX	OMX	EEX	ECX	OMX	EEX
Median	0.0066	0.0174	0.0115	0.0013	0.0239	0.1850	0.0033	0.0137	0.0072

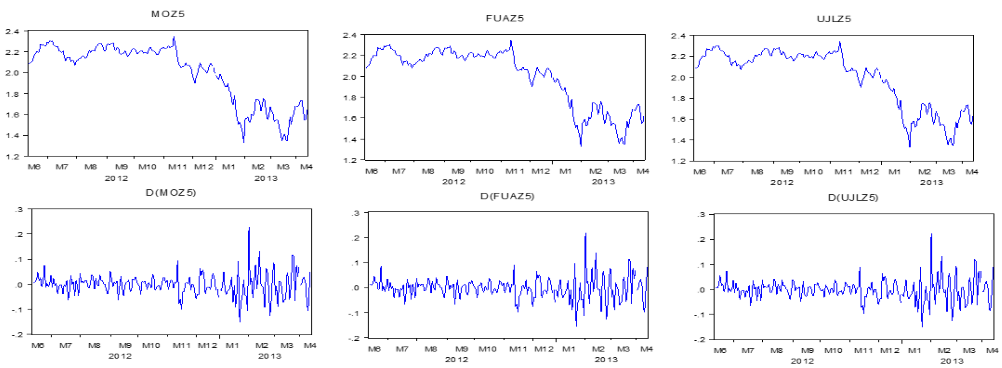
Figure 1: Transaction prices and log returns for the three futures contracts on the three platforms - Time series



(a)



(b)



(c)

Panel a, b and c present the time series of the transaction prices on the first line and the corresponding log returns on the second line for the Dec 2013, 2014, 2015 futures contracts respectively. The first / second / third column refers to the ICE-ECX / NASDAQ OMX / EEX platform, respectively (with the corresponding Bloomberg tickers: MOZ / FUAZ / UJLZ).

Table 5: VECM Model selection Rank of the VECM

		Daily Trade prices			Intraday Mid quotes		
Maturity		Dec-13	Dec-14	Dec-15	Dec-13	Dec-14	Dec-15
SIC		-20.84	-20.60	-19.42	-11.09	-12.06	-12.12
Optimal K		1	1	1	1	1	3
VECM	*Data Trend*	None	None	None	None	None	None
	Coint. Vector	No Intercept No Trend	No Intercept No Trend	No Intercept No Trend	No Intercept No Trend	No Intercept No Trend	No Intercept No Trend
Nb of coint. vectors	*Trace test*	2	2	2	2	2	2
	Max. Eigen value	2	2	2	2	2	2

Table 6: VECM long-term dynamics of daily log transaction prices

Trade prices	Benchmark exchanges	Cointegrating vector β_1	β_2	β_3	δ_1	δ_2	δ_3
Maturity Dec-13	*ECX (1)*	1.0000	-14.4400***	13.4396***	-0.0257	0.05561*	-0.0150
			(0.7837)	(0.7836)	(0.0329)	(0.0327)	(0.0325)
	OMX (2)	-0.0693	1.0000	-0.9307***	-0.3705	-0.8029*	0.2168
		(0.0562)		(0.0562)	(0.4757)	(0.4719)	(0.4686)
	EEX (3)	0.0744	-1.0744***	1.0000	0.3449	0.747329*	-0.2018
		(0.0672)	(0.0672)		(0.4428)	(0.4393)	(0.4362)
Maturity Dec-14	*ECX (1)*	1.0000	2.5107***	-3.5098***	-0.0848	-0.1937	0.0973
			(0.1788)	(0.1788)	(0.1283)	(0.1273)	(0.1260)
	OMX (2)	0.3983	1.0000	-1.3980***	-0.2129	-0.4862	0.2443
		(0.0853)		(0.0853)	(0.3222)	(0.3195)	(0.3163)
	EEX (3)	-0.2849***	-0.7153***	1.0000	0.2977	0.6797	-0.3415
		(0.0584)	(0.0584)		(0.4504)	(0.4466)	(0.4421)
Maturity Dec-15	*ECX (1)*	1.0000	1.8401***	-2.8388***	-0.3824	-0.4605	-0.0917
			(0.2648)	(0.2647)	(0.3685)	(0.3654)	(0.3597)
	OMX (2)	0.5434***	1.0000	-1.5427***	-0.7036	-0.8473	-0.1687
		(0.1575)		(0.1573)	(0.6781)	(0.6723)	(0.6619)
	EEX (3)	-0.3523***	-0.6482***	1.0000	1.0855	1.3071	0.2603
		(0.1184)	(0.1183)		(1.0461)	(1.0372)	(1.0212)

Subscripts 1, 2, and 3 relate to ICE-ECX, NASDAQ OMX, and EEX exchanges, respectively.

Table 7: VECM short-term dynamics of daily log transaction prices

	Dec-13			Dec-14			Dec-15		
	$\Delta p_{1,t}$	$\Delta p_{2,t}$	$\Delta p_{3,t}$	$\Delta p_{1,t}$	$\Delta p_{2,t}$	$\Delta p_{3,t}$	$\Delta p_{1,t}$	$\Delta p_{2,t}$	$\Delta p_{3,t}$
$\Delta p_{1,t-1}$	-0.2772	0.2488	0.2055	0.0871	0.6003*	0.4459	0.5486	1.0220	0.9193
	(0.3528)	(0.3500)	(0.3475)	(0.3283)	(0.3255)	(0.3223)	(0.7709)	(0.7643)	(0.7525)
$\Delta p_{2,t-1}$	0.3868	0.0689	0.1320	0.2777	-0.0312	0.0865	0.2565	-0.1506	-0.0083
	(0.3752)	(0.3722)	(0.3696)	(0.3123)	(0.3097)	(0.3066)	(0.7353)	(0.7290)	(0.7178)
$\Delta p_{3,t-1}$	-0.0715	-0.2763	-0.2932	-0.3395	-0.5268	-0.4977	-0.7327	-0.7888	-0.8330
	(0.3502)	(0.3474)	(0.3449)	(0.3464)	(0.3435)	(0.3401)	(0.7430)	(0.7366)	(0.7253)

Subscripts 1, 2, and 3 relate to ICE-ECX, NASDAQ OMX, and EEX exchanges, respectively. To save space, we only report the short-term dynamics when ICE-ECX is taken as the benchmark exchange.

Table 8: VECM long-term dynamics of hourly log mid quotes

Mid quotes	Benchmark exchanges	Cointegrating vector β_1	β_2	β_3	δ_1	δ_2	δ_3
Maturity Dec-13	*ECX (1)*	1	-0.3393***	-0.6608***	-0.38***	0.8328***	0.9606***
			(0.0523)	(0.0523)	(0.0327)	(0.0462)	(0.0452)
	OMX (2)	-2.9474***	1	1.9475***	0.1289***	-0.2826***	-0.3259***
		(0.0902)		(0.0903)	(0.0111)	(0.0157)	(0.0153)
	EEX (3)	-1.5134***	0.5135***	1	0.2511***	-0.5503***	-0.6347***
		(0.0483)	(0.0483)		(0.0216)	(0.0305)	(0.0298)
Maturity Dec-14	*ECX (1)*	1	-0.1082***	-0.8919***	-0.9143***	0.0027	0.0131
			(0.0227)	(0.0227)	(0.0414)	(0.0828)	(0.0774)
	OMX (2)	-9.2403***	1	8.2418***	0.0989***	-0.0003	-0.0014
		(0.2439)		(0.2441)	(0.0045)	(-0.009)	(0.0084)
	EEX (3)	-1.1212***	0.1213***	1	0.8155***	-0.0024	-0.0117
		(0.0209)	(0.0209)		(0.0369)	(0.0739)	(0.0691)
Maturity Dec-15	*ECX (1)*	1	-2.0995***	1.1002***	-0.3307***	0.0782	-0.2215***
			(0.1046)	(0.1046)	(0.0296)	(0.0893)	(0.0851)
	OMX (2)	-0.4763***	1	-0.524***	0.6944***	-0.1641	0.4651***
		(0.0335)		(0.0335)	(0.0621)	(0.1874)	(0.1786)
	EEX (3)	0.9089***	-1.9083***	1	-0.3639***	0.086	-0.2437***
		(0.0664)	(0.0663)		(0.0325)	(0.0982)	(0.0936)

Subscripts 1, 2, and 3 relate to ICE-ECX, NASDAQ OMX, and EEX exchanges, respectively.

Table 9: VECM short-term dynamics of hourly log mid quotes

Mid	Dec-13			Dec-14			Dec-15		
quotes	$\Delta p_{1,t}$	$\Delta p_{2,t}$	$\Delta p_{3,t}$	$\Delta p_{1,t}$	$\Delta p_{2,t}$	$\Delta p_{3,t}$	$\Delta p_{1,t}$	$\Delta p_{2,t}$	$\Delta p_{3,t}$
$\Delta p_{1,t-1}$	0.0456**	0.1541***	0.1447***	0.0856***	0.0768**	0.1296***	-0.1747***	-0.1521	0.0108
	(0.0217)	(0.0307)	(-0.03)	(0.0194)	(0.0387)	(0.0362)	(0.0318)	(-0.096)	(0.0915)
$\Delta p_{2,t-1}$	0.3250***	0.1069**	0.5744***	0.2094***	0.1179*	0.4277***	-0.2301***	-0.026	0.1684
	(0.0318)	(-0.045)	(-0.044)	(0.0302)	(0.0605)	(0.0566)	(0.0574)	(0.1733)	(0.1651)
$\Delta p_{3,t-1}$	0.0615*	0.4293***	0.0722*	-0.1397***	-0.033	-0.3268***	0.8369***	0.2601**	-0.2580**
	(0.0315)	(0.0445)	(0.0436)	(0.0387)	(0.0775)	(0.0724)	(0.0383)	(0.1157)	(0.1102)

To save space, we only report the short-term dynamics for the first lag, when ECX is taken as the benchmark exchange.

Table 10: Indirect effects (on hourly log mid quotes)

	Dec-13		Dec-14		Dec-15	
Null Hypothesis (H0)	Wald Stat	P-value	Wald Stat	P-value	Wald Stat	P-value
ECX returns not affected by OMX and EEX	243.6788	<0.0001	48.7989	<0.0001	5936.561	<0.0001
OMX returns not affected by ECX and EEX	143.2052	<0.0001	3.97939	0.1367	20.6936	<0.01
EEX returns not affected by ECX and OMX	229.1883	<0.0001	75.4171	<0.0001	55.5212	<0.0001

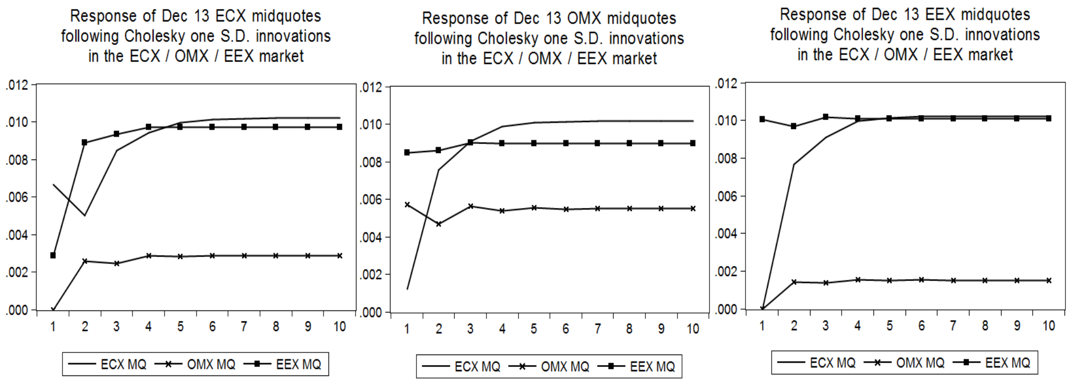
The Wald statistics are calculated using Newey and West's heteroskedascity and autocorrelation consistent variance-covariance matrix. The null model includes only own index security effects (i.e., own lags). In this application the test statistics are $\chi^2(12)$ distributed.

Table 11: Accounting for Innovations and Variance decompositions (on hourly log mid quotes)

Horizon (in periods)	Dec-13								
	Ordering: ECX/OMX/EEX			Ordering: OMX/ECX/EEX			Ordering: EEX/ECX/OMX		
	ECX	OMX	EEX	OMX	ECX	EEX	EEX	ECX	OMX
1	100	0	0	100	0	0	100	0	0
2	72.39	25.68	1.93	83.93	15.88	0.18	76.11	23.1	0.79
3	76.07	22.46	1.47	77.52	21.84	0.63	67.16	31.97	0.88
4	78.1	20.8	1.09	73.4	25.79	0.81	61.78	37.26	0.96
5	79.69	19.43	0.89	71.08	27.97	0.95	58.74	40.27	0.99
10	82.43	17.05	0.53	66.81	32	1.2	53.25	45.7	1.05
20	83.5	16.11	0.39	64.96	33.73	1.3	50.88	48.04	1.08
Horizon (in periods)	Dec-14								
	Ordering: ECX/OMX/EEX			Ordering: OMX/ECX/EEX			Ordering: EEX/ECX/OMX		
	ECX	OMX	EEX	OMX	ECX	EEX	EEX	ECX	OMX
1	100	0	0	100	0	0	100	0	0
2	76.14	20.07	3.79	99.98	0.02	0.01	98.64	0.21	1.16
3	71.43	24.74	3.82	99.98	0.01	0.01	98.61	0.15	1.24
4	69.46	26.61	3.93	99.98	0.01	0.01	98.51	0.12	1.37
5	68.46	27.57	3.97	99.99	0.01	0.01	98.47	0.1	1.43
10	66.81	29.16	4.03	99.99	0.01	0.01	98.38	0.08	1.55
20	66.14	29.8	4.06	99.99	0	0.01	98.34	0.06	1.6
Horizon (in periods)	Dec-15								
	Ordering: ECX/OMX/EEX			Ordering: OMX/ECX/EEX			Ordering: EEX/ECX/OMX		
	ECX	OMX	EEX	OMX	ECX	EEX	EEX	ECX	OMX
1	100	0	0	100	0	0	100	0	0
2	65.51	33.18	1.32	99.63	0.073	0.3	98.74	0.06	1.19
3	57.84	41.46	0.7	99.09	0.25	0.66	98.61	0.35	1.04
4	55.01	44.41	0.58	98.89	0.3	0.81	98.54	0.43	1.03
5	53.81	45.7	0.49	98.82	0.33	0.85	98.45	0.49	1.05
10	51.98	47.69	0.34	98.68	0.38	0.94	98.33	0.59	1.08
20	51.25	48.47	0.28	98.61	0.41	0.98	98.28	0.63	1.09

Entries are fractions of the forecast error variance at horizon h that are attributable to common factor shocks (with three different orderings).

Figure 2: Impulse responses to Choleski one S.D. Innovations



The three graphs present the responses to Choleski one S.D. Innovations for December 2013 contracts on the three exchanges. The chosen order is ECX/OMX/EEX, but the results are absolutely insensitive to any order switch.