University of Heidelberg

Department of Economics

Discussion Paper Series | No. 492

# Price Discovery, Causality and Volatility Spillovers in European Union Allowances Phase II: A High Frequency Analysis

Daniel Rittler

November 2009

# Price Discovery, Causality and Volatility Spillovers in European Union Allowances Phase II: A High Frequency Analysis*

Daniel Rittler†

October 2009

**Abstract**

This paper deals with the modeling of the relationship of European Union Allowance spot- and futures-prices within the second commitment period of the European Union Emission Trading Scheme. Based on high frequency data, we analyze causality in the first and the second conditional moments. To reveal long run price discovery we compute the common factor weights proposed by Schwarz and Szakmary (1994) and the information share proposed by Hasbrouck (1995) based on the estimated coefficients of a vector error correction model. To analyze the short run dynamics we perform Granger causalty tests. The GARCH-BEKK model introduced by Engle and Kroner (1995) is employed to analyze the volatility transmission structure. We identify the futures market to be the leader of the long run price discovery process whereas a bidirectional short run causality structure is observed. Furthermore we detect unidirectional volatility transmission from the futures to the spot market at highest frequencies.

**Keywords**: CO2 Emission Allowances, Causality, Volatility Transmission, Spot Prices, Futures Prices

**JEL Classification**: G13, G14, G15, G17

*I would like to thank Christian Conrad for his valuable suggestions.

†Daniel Rittler, Department of Economics, University of Heidelberg, Bergheimer Straße 20, 69115 Heidelberg, Germany, E-Mail: daniel.rittler@awi.uni-heidelberg.de; Phone: +49/6221/54/5093.

# 1 Introduction

Since the implementation of the European Union Emissions Trading Scheme (EU ETS) in January 2005 the trading volume within the futures markets for European Union Allowances (EUA) has steadily expanded over the first two commitment periods. However, as a consequence of the overallocation with EUAs in the first commitment period the transaction volume in the spot market strongly decreased within the first commitment period. At the begining of the second commitment phase spot market turnover stongly rose and was even higher compared to the period prior to the spot market collapse. This paper analyzes causality in the conditional mean and the conditional variance of carbon spot and futures prices within Phase II of the EU ETS based on highly informative intraday data. Concerning the price transmission mechanisms, we proceed in two steps. First, we perform a long run price discovery analysis. Following the literature on price discovery we compute the common factor weights proposed by Schwarz and Szakmary (1994) as well as the information share developed by Hasbrouck (1995). Second we analyze the short run dynamics causality structure performing Granger (1969) causality tests. To analyze causality in the second conditional moment, we use the multivariate BEKK-GARCH specification introduced by Engle and Kroner (1995).

The results of our analysis provide evidence that in the early state of Phase II the long run price discovery process takes place in both, the spot and the futures market whereas at least at highest frequencies the futures market's relevance in the long run price discovery process exceeds the spot market's relevance. In the short run dynamics context the futures market can be identified as predominant price leader. The situation changes as the markets become more mature. At each of the analyzed frequencies the futures market can be identified as long run price leader. The speed of adjustment to the equilibrium price path in the case of disequilibria strongly increases as the EU ETS Phase II beocmes more mature. A bidirectional short run dynamics structure is observed. Analyzing the volatility transmission structure as well yields the result of unidirectional volatility spillovers from the futures to the spot market at the highest analyzed frequency of 10 minutes. Furthermore the results show that an intraday anylysis is required to capture the transmission structures in the first and the second conditional moments.

Previous studies such as Uhrig-Homburg and Wagner (2007) or Milunovich and Joyeux (2007) have focused the analysis on the first commitment period using daily, and hence, less informative data. Since the markets are much more mature by now and the transaction volume has strongly increased, an extension of the daily analysis to a high-frequency level should deepen the understanding of the microstructure of the European carbon markets.

The remainder of the paper is organized as follows. Section 2 gives a short description of the European Union Emissions Trading Scheme and related work. Section 3 briefly describes the data used in the empirical analysis and gives an overview of the relationship between commodity spot and futures prices in general. In Section 4, we outline the methodology used in the empirical analysis. Section 5 summarizes the results of the econometric specifications. Finally, Section 6 concludes.

# 2 The European Union Emissions Trading Scheme

## 2.1 Framework of the Trading Scheme

In January 2005 the European Union Emission Trading Scheme, driven by the Directive 2003/87/EC, formally entered into operation. Within the framework of the Kyoto Protocol the European Union has established the EU ETS with the ultimative objective to reduce greenhouse gas emissions in a cost efficient way. To fullfill their commitments, the European Community and its Member States agreed to construct an efficient European market for European Union Allowances. One EUA warrants the right to emit one tonne of $CO_2$-equivalent, whereas next to carbon dioxide the EU ETS also covers further anthropogenic greenhouse gases that are supposed to have an impact onto climate change.[1]
The EU ETS is organized in several comittment periods. The first period lasted from 2005 to 2007 and served as a pilot period. The second period lasting from 2008 to 2012 coincidences with the first Kyoto commitment period. The third period covers the years 2013 to 2020.
The market is designed as a cap and trade market. All participating installations, companies operating in the sectors production and processing of steel and iron, minerals, energy or pulp and paper, are grandfathered and/or auctioned a certain volume of emission allowances to meet their compliance requirements, according to the cap determined by the European Commission.[2] The caps that the European Commission determines are fixed in National Allocation Plans (NAP), published by the European Commission and contain the volume of assigned emission allowances as well as the receipting installations. Having been assigned, it is possible to trade emission allowances freely in many organized market places within the EU ETS. In April 30 of each year each participating installa-

[1]Besides carbon dioxide, the EU ETS accounts for methane, nitrous oxide, hydro fluorocarbons, perfluorocarbons and sulphur hexafluoride.

[2]With the start of Phase III in 2013, the allocation of allowances should in principle take place on the basis of auctions. With the start of Phase III in 2013, the aviation sector's emissions are planned to be covered by the EU ETS as well.

tion has to provide the quantity of EUAs for the previous year. Installations that have spare number of allowances can sell them on the market. Inversely, any installation that lacks allowances has to purchase them from other installations or market participants. All emissions that are not covered by surrendered EUAs or other eligible instruments are fined with 40 €/tCO2e (in Phase I) or 100 €/tCO2e (in Phase II) and additionally have to be turned in at the next compliance date.
Within the EU ETS all participating installations are allowed to use other eligible instruments, the so called Certified Emission Reductions (CERs) or Emission Reduction Units (ERUs), instead of EUAs to meet their compliance requirements. CERs can be obtained by carrying out emission reduction projects within the framework of the Clean Development Mechanism (CDM). ERUs are granted for emission reductions that are achieved under the so called Joint Implementation (JI). Both mechanisms are defined under the Kyoto Protocol and refer largely either to projects that are conducted between developed and developing countries or developed countries only. The usage of alternative credits from the Clean Development Mechanism or Joint Implementation is subject to limits. The limits are defined as a percentage of the member state's allowed cap and sets the maximum number of CERs or ERUs that may be surrendered for compliance by participating installations.

## 2.2 Related Work

The largest strand of existing literature relates a wide range of environmental economics related questions, concerning the design of the national allocation plans (Boeringer et al. (2005)), the allocation procedure (Cramton and Kerr (2002)), aspects of competitiveness (Oberndorfer and Rennings (2006)), or the effects of banking restrictions between Phase I and Phase II (Alberola and Chevallier(2009a) and Alberola and Chevallier(2009b)). Besides those, there have been a few studies concerned with price discovery, liquidity or the trading process. The major part of the existing studies investigates price formation and price discovery within the first commitment period using data on a daily basis. Early analyses on a daily basis, such as Mansanet-Bataller et al. (2007) and Alberola et al. (2008) analyze the impact of the market fundamentals oil, natural gas and coal, as well as weather, on the daily EUA log returns in the early stage of the EU ETS, following Christiansen and Arvanitakis (2004) who argue that the best way to forecast trends in carbon prices is to assess policy and regulatory issues, market fundamentals and technical analysis. Using an autoregressive distributed lag model (neglecting ARCH-effects), Mansanet-Bataller et al. (2007) conclude that the most important factors driving EUA prices are the prices for coal and natural gas. Alberola et al. (2009) extend the framework

of Mansanet-Bataller et al. (2007) by controlling additionally for sectoral production. In line with Mansanet-Bataller et al. (2007) the authors conclude that the main driving factors are fuel prices. Furthermore they show that sectoral production also affects the EUA price. Mansanet-Bataller and Padro (2007) highlight the impact of regulatory issues, analyzing the effect of NAPs on the carbon prices. The authors use an event study methodology, whereas they employ dummy variables to represent the event of a NAP announcement, released by the European Commission, within a certain day. Mansanet-Bataller and Padro (2007) conclude that the release of NAP announcements has an influence on the EUA price within the day of the release and the preceding day. In one of the first papers taking ARCH-effects into account, Benz and Truck (2009) model the EUA daily price dynamics using GARCH-type and Markov-switching models.
Uhrig-Homburg and Wagner (2007) investigate the relationship of EUA spot and futures prices within the framework of a cost-of-carry model, neglecting convenience yields for economic reasons.[3] Using a vector error correction model, Uhrig-Homburg and Wagner (2007) compute price discovery measures and identify the futures market as price leader. Uhrig-Homburg and Wagner (2007) restrict their analysis to price transmission between the spot and futures market. Causality in the second conditional moment is not analyzed. Due to the low data availibility within the early stage of the EU ETS the authors do have to run their analysis on daily data. In a further article Borak et al. (2006) investigate the existence of convenience yiels within the first commitment period using daily data and GARCH-type models. As already mentioned, there have been only very few studies addressing the EUA intraday price formation. One of those is Benz and Hengelbrock (2008) who use the Engle and Granger (1987) framework to estimate an error correction model to analyze the joint development of EUA futures prices observed on the ECX and the Nord Pool, respectively. Rotfuß (2009) and Chevallier and Sevi (2009) provide an overview of the intraday price behaviour of emmission allowances and model the realized volatility of the EUA spot and futures and the EUA futures, respectivly. Conrad et al. (2009) analyze the EUA return series' intraday reaction to the release of new information using a fracionally integrated asymmetric FIAGARCH model. Analyzing ECX futures market data the authors propose a model to quantify the surprise component in released news instead of using dummy variables and conclude that there is evidence of an impact of the release of relevant regulatory news, which extends the results of Mansanet-Bataller and Padro (2007).

[3] Uhrig-Homburg and Wagner (2007) argue that participating installations do have to fullfill their commitments only once a year. Within all other days, there is no benefit of holding emission allowances in terms of meeting unexpected demand to keep the production process going.

# 3 Data

## 3.1 Spot- and Futures Markets

The European market for emission allowances is organized as an over-the-counter market as well as an on exchange market, whereas according to Point Carbon (2008) 70 percent of the total number of transactions take place over-the-counter and only 30 percent are split up between the ECX (London), the NordPool (Oslo), the EEX (Leipzig), the Eurex (Stuttgart), the BlueNext (Paris), the EXAA (Vienna) and the Climex (Utrecht). Additionally to spot market trading, some of the exchanges offer the possibility of trading EUA futures and further derivatives. To analyze price discovery, causality and volatility spillovers, we have to construct time series based on spot market trading and based on futures market trading. For the spot market series we use tick-by-tick data provided by the BlueNext, which represents about 70 percent of the total daily spot market transaction volume (Rotfuß (2009)) and for the futures market series we use tick-by-tick data provided by the ECX, which pepresents about 90 percent of the total daily futures market transaction volume. Hence, our analysis covers a substantial portion of exchange based trading. Since we are interested in the price discovery process within the second Phase of the EU ETS, we only consider transactions within the period 01/05/2008 to 18/03/2009 whereas we concentrate on the futures contract with maturity in December 2008 and in December 2009, respectively. Since the deadline for submitting emission allowances for the preceding year's emissions is on 30 April of the consecutive year, the trading period corresponding to Phase I does not end on 31/12/2007 but on 30/04/2008. Hence, we do not consider transactions before 01/05/2008. Before March 2009, spot market trading took place from 07:00 to 15:00 GMT. From March 2009 onwards, spot market trading time has been extended to 06:00 to 15:30 GMT. Hence, our sample only covers 14 trading days of the extended timeframe of spot market trading. Trading in the futures market is feasible from 06:00 to 16:00 GMT. To exclusively consider the trading period where spot as well as futures market trading is possible, we restrict the daily series within the empirical analysis to 07:00 to 15:00 GMT. We transform the original unregular price data to equidistant intraday log prices at frequencies $h = 10$ and 30 minutes. Taking the immediately preceding and following quote at the end of each $h$-minute interval we compute the mean to get the log price at the $h$-minute mark. If the observed time stamp of the transaction equals the $h$-minute mark we use the corresponding price as the equidistant intraday price at frequency $h$. If there is no transaction at the first $h$-minute mark at 07:00 the first intraday price equals the last price of the preceding trading day.[4] In general to avoid overnight effects we do not take the mean of transaction prices of two different days. The price of the last $h$-minute mark of the trading day at 15:00 equals the price of the last observed transaction before 15:00.

## 3.2 Relating EUA Spot and Futures Prices

A considerable fraction of the commodity pricing literature has been done on the interlinkage between spot and futures prices of particular commodity goods. According to Fama and French (1987), valuation of futures contracts can be seperated into two approaches. The first approach uses a risk premium to model the relationship between spot and futures prices. The second approach directly investigates the cost and benefit of holding a commodity good. Due to the no-arbitrage condition, the interlinkage of a commodity good's spot and futures price should be modeled within the framework of a cost-of-carry model. Generally, the cost-of-carry relationship states

$$p_t^F(T) = e^{(r_t - \delta_t)(T-t)} p_t^S, \tag{1}$$

whereas $p_t^F(T)$ denotes the observed futures price at $t$ of a contract with maturity in $T$, $p_t^S$ denotes the spot price in $t$, $r_t$ states the risk-free interest rate in $t$ and, following Brennan (1991), $\delta_t$ is called the convenience yield in $t$. On the one hand, there is a negative effect of holding a commodity good in the form of forgone interest yields and storage costs. On the other hand, there is a positive effect of holding the commodity good due to uncertainty caused by fluctuations in supply and demand, whereas the benefit is reasoned by the opportunity of meeting unexpected demand in the production process.

The cost-of-carry relationship as stated above holds for a range of commodity goods and has to be proved in the case of the European Union allowance market.[5] As explained by Uhrig-Homburg and Wagner (2007) and Borak et al. (2006), contrary to other production factors, like raw materials or energy, emission allowances are only needed once a year to fulfill compliance requirements. Hence, Uhrig-Homburg and Wagner (2007) argue that there is no economic rationale for the existence of convenience yields in the European

[4] With regard to potential problems induced by interday volatility effects we estimated the models outlined in section 4 based on observations from 07:30 to 15:00 GMT as well. The results are very similar to those reported in section 5.

[5] The cost-of-carry relationship holds within markets for intertemporally storable commodity goods like gold or oil. Caution is advised when modelling the relation of intertemporally non-storable commodity goods within the cost-of-carry framework.

Union allowance market. The authors also argue that there are no storage costs and thus conclude that the relationship between spot and futures prices can be derived by

$$p_t^F(T) = e^{r_t(T-t)} p_t^S. \tag{2}$$

We now compare the theoretical futures price $p_t^{TF}(T) = e^{r_t(T-t)} p_t^S$ with the observed

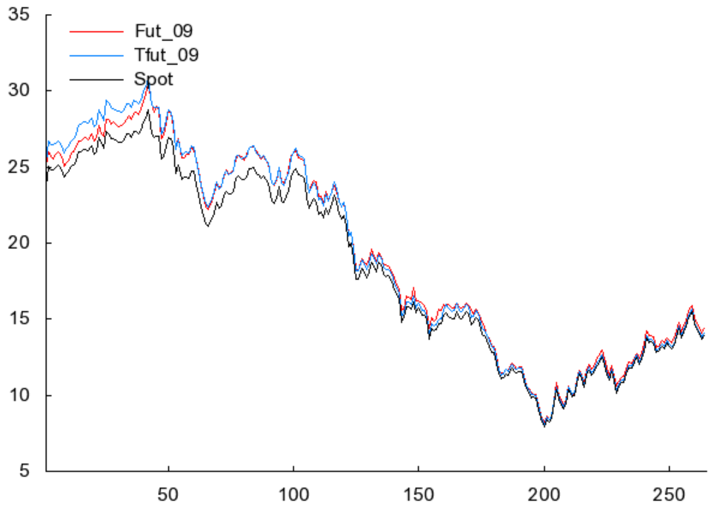


Figure 1: Cost-of-Carry Relationship: Contract with maturity in Dec 2009

futures price $p_t^F(T)$ which should be identical if the cost-of-carry relationship without convenience yields holds. The risk-free interest rate $r_t$ used in the empirical analysis is the monthly EURIBOR on a daily basis. Observing theoretical futures prices lying above observed futures prices could be evidence for the existence of convenience yields. Using the emissions market data described above, we show the relationship between the observed futures price of the contract with maturity in December 2009 and the theoretical futures price derived within the cost-of-carry-model neglecting convenience yields in Figure 1.[6] Additionally to the observed and theoretical prices, the spot price is also pictured in Figure 1. Figure 1 shows that within the first two months of Phase II the theoretically derived futures price lies above the observed futures price. From 01/07/08 on, the relationship between the theoretical and the observed futures price postulated within the cost-of-carry model holds almost exactly. Within the whole period of observation, the spot price lies

[6]Besides the illustrated contract with maturity in December 2009, we also observed the circumstance that the observed futures price of the contract with maturity in December 2008 was located underneath the theoretical futures price according to the cost-of-carry relationship within the period from 02/05/08 to 30/06/08. Again, from 01/07/08 the observed futures price and the theoretical futures price are virtually identical.

clearly underneath the observed futures prices, whereas the difference decreases as the time to maturity decreases.

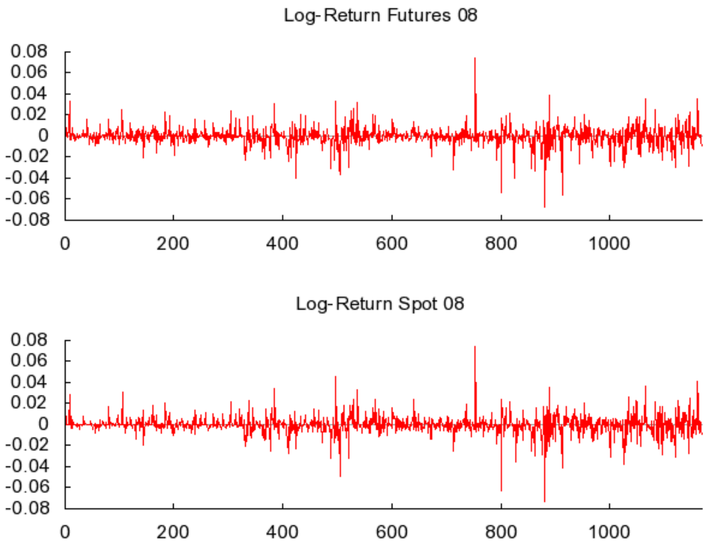


Figure 2: Log-Returns in the spot and futures market based on the contract with maturity in December 2008 and frequency $h = 60$ minutes.

Figure 2 shows the log returns in the spot and the futures market based on the contract with maturity in December 2008 and frequency $h = 60$ minutes. The graphs clearly exhibit volatility clustering. Furthermore a first visual inspection gives evidence that the evolution of the volatility in both markets are closely linked. Periods of high (low) volatility in the futures market are accompanied by periods of high (low) volatility in the spot market. That of course has to be proven by much more sophisticated methods described and applied in the following both sections.

# 4 Methodology

In this section we describe the models used to investigate price discovery, causality and volatility transmission in the spot and futures markets. We make use of a two step sequential estimation procedure. In the first step we estimate a vector error correction model within the Engle and Granger (1987) framwork, using the series of the theoretically derived futures prices and the series of the empirically observed futures prices. Afterwards, we compute price discovery measures based on common factors introduced by Schwarz and Szakmary (1994) and by Hasbrouck (1995). Furthermore we perform Granger causality tests (Granger (1969)) to recover price transmission mechanisms between spot and futures markets regarding the conditional mean of both series. Finally, we use the residuals of the first estimation step to estimate a multivariate BEKK-GARCH model, introduced by Engle and Kroner (1995), to investigate volatility spillovers between spot and futures markets.

## 4.1 Estimating the Vector Error Correction Model

Let $p_t = (p_t^{TF}\ p_t^F)'$ be the two-dimensional price vector containing the theoretical futures price $p_t^{TF}$ and the observed futures price $p_t^F$. The series $p_t^{TF}$ and $p_t^F$ are said to be cointegrated (Engle and Granger (1987)) of order $d$ and $b$, denoted $p_t \sim CI(d,b)$, if ($i$) all components of $p_t$ are $I(d)$ and ($ii$) a vector $\beta \neq 0$ exists, such that $z_t = \beta p_t \sim I(b), b > 0$. We assume each of the individual series to be at most $I(1)$.[7] The vector $\beta$ is called the cointegrating vector. Consider the vector autoregressive (VAR) model of order $p$

$$p_t = \mu + \sum_{i=1}^{p} A_i p_{t-i} + \varepsilon_t, \tag{3}$$

whereas $p_t$ is the $(2 \times 1)$ vector introduced above, the matrices $\{A_i\}_{i=1}^p$ are the $(2 \times 2)$ coefficient matrices of the lagged endogenous variables, $\mu$ is a $(2 \times 1)$ vector of constants. The $(2\times1)$ error term $\varepsilon_t$ is assumed to be $i.i.d.$ as $\varepsilon_t \sim N(0,\Omega)$, whereas $\Omega$ is the covariance matrix of the error term. Following the Granger Representation Theorem the cointegrated series $p_t^{TF}$ and $p_t^F$ have a vector error correction model (VECM) representation of infinite order which can be approximated by the finite order VECM$(p-1)$

$$\Delta p_t = \mu + \Pi p_{t-1} + \sum_{i=1}^{p-1} \Gamma_i \Delta p_{t-1} + \varepsilon_t, \tag{4}$$

whereas $\Pi = -A(1) = -(I - \sum_{i=1}^{p} A_i)$ and $\Gamma_i = -\sum_{j=i+1}^{p} A_j$. The matrix $\Pi p_{t-1} \sim I(0)$ states the long run relationship, the matrices $\{\Gamma_i\}_{i=1}^{p-1}$ contain the short run dependencies. If $\Pi$ is singular with $rk(\Pi) = r$ and $\Pi = \alpha\beta'$ with $rk(\alpha) = rk(\beta) = r$ then $\beta$ is called the cointegrating matrix and $\alpha$ is called the loading matrix, that controls the speed of adjustment to the long run equilibrium. Again, $\mu$ is a vector of constants and $\varepsilon \sim N(0,\Omega)$, whereas $\Omega$ is the covariance matrix of the error term. Following the efficient-market hypothesis (Fama(1970)) the series should not drift to far appart since the available information should be reflected in both price series because both series reflect an equivalent asset. Therefore we restrict the cointegrating vector $\beta$ to $\beta = (1\ -1)'$.[8] Having restricted

[7] In the empirical analysis we use ADF and KPSS tests to determine the degree of integration to confirm the series being at most $I(1)$.

[8] In the empirical analysis we also estimate the cointegrating vector $\beta$ to justify the choice of $\beta = (1\ -1)'$.

the cointegrating vector to $\beta = (1\ {-1})'$ the matrix notation of the VECM can be expanded to

$$\Delta p_t^{TF} = \mu^{TF} + \sum_{i=1}^{p-1} \gamma_{11,i} \Delta p_{t-i}^{TF} + \sum_{i=1}^{p-1} \gamma_{12,i} \Delta p_{t-i}^{F} + \alpha^{TF}(p_{t-1}^{TF} - p_{t-1}^{F}) + \varepsilon_t^{TF} \tag{5}$$

$$\Delta p_t^{F} = \mu^{F} + \sum_{i=1}^{p-1} \gamma_{21,i} \Delta p_{t-i}^{TF} + \sum_{i=1}^{p-1} \gamma_{22,i} \Delta p_{t-i}^{F} + \alpha^{F}(p_{t-1}^{TF} - p_{t-1}^{F}) + \varepsilon_t^{F} \tag{6}$$

Due to its stationarity, the process $\Delta p_t$ has a Wold representation and can be expressed as a vector moving average (VMA) process

$$\Delta p_t = \sum_{s=0}^{\infty} \Psi_s L^s \varepsilon_t = \Psi(L)\varepsilon_t, \tag{7}$$

whereas $\Psi_0 = I$. The elements $\{\Psi_s\}_{s=0}^{\infty}$ of the matrix polynomial $\Psi(L)$ are 1-summable and $\Psi(z)$ is of full rank everywhere on $|z| \leq 1$. $rk(\Psi(1)) = 1$, $\beta'\Psi(1) = 0$ and $\Psi(1)\alpha = 0$. Applying the Beveridge-Nelson decomposition and iterarting backwards yiels the relationship in levels

$$p_t = \Psi(1) \sum_{j=1}^{t} \varepsilon_j + \Psi^*(L)\varepsilon_t, \tag{8}$$

whereas $\Psi(1) = \sum_{s=0}^{\infty} \Psi_s$ and $\Psi_s^* = -\sum_{j=s+1}^{\infty} \Psi_j$. The elements of the $(2 \times 2)$ moving average impact matrix $\Psi(1)$ are the cumulative VMA coefficients. $\Psi(1)\varepsilon_t$ measures the long run impact on each of the prices of the innovation in $t$. Due to the orthogonality of $\beta$ and $\Psi$ and the restricted cointegrating vector $\beta = (1\ {-1})'$, the moving average impact matrix contains identical rows, implicating identical long run impacts of an innovation on the prices in both markets. Defining $\psi = (\psi_1\ \psi_2)$ as the common row vector of $\Psi(1)$ the VMA in levels can be written as

$$p_t = \begin{pmatrix} 1 \\ 1 \end{pmatrix} \psi \sum_{j=1}^{t} \varepsilon_j + \Psi^*(L)\varepsilon_t. \tag{9}$$

Hasbrouck (1995) defines $(1\ 1)'\psi \sum_{j=1}^{t} \varepsilon_j \sim I(1)$ as the common trend that describes the common efficient price in the two markets. The second term $\Psi^*(L)\varepsilon_t \sim I(0)$ describes the transitory portion of the price change.

## 4.2 Price Discovery Measures and Causality Analysis

Based on the estimation results of the first step, we are able to estimate the most commonly used price discovery measures, the common factor weights proposed by Schwarz and Szakmary (1994) and the information shares introduced by Hasbrouck (1995). Furthermore we employ the concept of Granger causality to investigate the lead lag structure of the conditional means in the spot and the futures market. The price discovery measures are based on the estimate of the coefficient on the error of the previous period. Hence, the common factor weigths as well as the information shares are measures that analyze the long run price discovery process. Contrary, Granger causality tests investigate the short run dynamics.

*Common Factor Weights*

Consider the loading matrix $\alpha$ of the VECM described above. Schwarz and Szakmary (1994) argue that the coefficients $\alpha^{TF}$ and $\alpha^{F}$ determine the permanent effect that a shock to one of the series has on the system. Consequently Schwarz and Szakmary (1994) propose to use the relative magnitude of the coefficients to assess the contribution of each market to the price discovery process. The common factor weights of the futures and the spot market are given by

$$CFW^{F} = \frac{|\alpha^{TF}|}{|\alpha^{TF}| + |\alpha^{F}|} \quad \text{and} \quad CFW^{TF} = \frac{|\alpha^{F}|}{|\alpha^{TF}| + |\alpha^{F}|}.\text{[9]} \tag{10}$$

Schwarz and Szakmary (1994) argue that the parameters measure the speed of assimilation to differences between the market prices. Therefore the sum of the coefficients measures the total adjustment to a shock in one or both markets. If the price discovery process exclusively takes place in one market the corresponding market's common factor weights takes on the value one. If each of the markets equally contributes to the price discovery process, the markets' commom factor weights are identical.

*Information Shares*

An often used measure in empirical work concerning price discovery is the information share proposed by Hasbrouck (1995). Consider the moving average impact matrix $\Psi(1)$ of the VMA representation derived by applying the Beveridge-Nelson decomposition to the VECM. Hasbrouck (1995) proposes a measure for the contribution of one market to the price discovery process based on the share of the variance $\psi'\Omega\psi$ of the permanent portion of the price change that is attributed to this market. Hence, if the VECM errors are uncorrelated, that means $\Omega$ is diagonal, the information share of market $i$ is defined as

$$IS_i = \frac{\psi_i^2 \sigma_{ii}}{\psi'\Omega\psi}, \tag{11}$$

whereas $\psi_i$ is the $i$th element of $\psi$ and $\sigma_{ii}$ is the $i$th diagonal element of $\Omega$. If there is contemporaneous residual correlation, that means $\Omega$ is not diagonal the problem of attributing the covariance terms to each market arises. To minimize the contemporaneous correlation, Hasbrouck (1995) suggests to compute the Cholesky decomposition $\Omega = FF'$, whereas $F$ is a lower tiangular matrix leading to the information share

$$IS_i = \frac{([\psi' F]_i)^2}{\psi' \Omega \psi} \tag{12}$$

of market $i$, whereas $[\psi' F]_i$ is the $i$th element of the row vector $\psi' F$. Depending on the ordering of the equations in the VECM different information shares are computed. An upper (lower) bound for market $i$'s information share is derived by ordering the price series of market $i$ first (second). Having computed the upper and lower bounds of the information shares, we build the arithmetic mean and compute each information share's range. This is in line with the usual modus operandi in the price discovery literature.

*Granger Causality Tests*

Additional to the described price discovery measures, we apply Granger causality tests as proposed by Granger (1969). Consider the two-dimensional price vector $p_t = (p_t^{TF}\ p_t^F)'$ and let $\mathcal{F}_t := \{p_t^{TF}, p_t^F, p_{t-1}^{TF}, p_{t-1}^F, \ldots, p_1^{TF}, p_1^F\}$ be an information set containing all observed price realizations. $p_t^{TF}$ Granger causes $p_t^F$ with respect to $\mathcal{F}_t$ if the optimal linear predictor of $p_{t+h}^F$ based on $\mathcal{F}_t$ has smaller variance than the optimal linear predictor of $p_{t+h}^F$ based on $\{p_t^F, p_{t-1}^F, \ldots, p_1^F\}$ for each $h$. Within the framework of the VECM, the concept of Granger causality is operationalized by testing if the lagged values of one series enter the equation of the other series statistically significant different from zero. Let the first equation of the VECM represent the futures market while the second equation of the model stands for the spot market. To check if the spot market Granger causes the futures market, we have to test the joint hypothesis

$$H_0 : \gamma_{21,1} = 0 \cap \ldots \cap \gamma_{21,p-1} = 0 \text{ against the alternative } H_1 : \exists \gamma_{21,i} \neq 0. \tag{13}$$

To check if the futures market Granger causes the spot market, we have to test the joint hypothesis

$$H_0 : \gamma_{12,1} = 0 \cap \ldots \cap \gamma_{12,p-1} = 0 \text{ against the alternative } H_1 : \exists \gamma_{12,i} \neq 0. \tag{14}$$

If the null hypothesis holds the corresponding market does not Granger cause the other market.

## 4.3 Volatility Spillovers

Despite the availability of a large range of empirically used univariate GARCH-type models to discover volatility spillovers, we prefer one of several more sophisticated multivariate

GARCH models to investigate volatility transmissions.[10] One specification that is used in the context is the VECH representaion of Bollerslev et al. (1988). A shortcome of the VECH model is the lagre number of parameters that have to be estimated. In the bivariate case there are 21 parameters to be estimated. The diagonal representation of the VECH model (Bollerslev et al. (1988)) requires fewer parameters to be estimated. The diagonal VECH model is improper to model volatility transmission since it assumes the individual conditional variances and covariances to depend on their own lags and squared residuals, only. Engle and Kroner (1995) proposed the BEKK representation, that assumes the following structure of the $(2 \times 2)$ conditional covariance matrix

$$H_t = CC' + \sum_{i=1}^{m} A_i(\varepsilon_{t-i}\varepsilon'_{t-i})A'_i + \sum_{j=1}^{s} B_j H_{t-j} B'_j, \tag{15}$$

where $C$ is an upper triangular matrix and $A_i$ and $B_j$ are $(k \times k)$ coefficient matrices, whereas $k$ represents the dimension of the series. Based on the symmetric parameterization of the model the conditional variance matrix $H_t$ is almost surely positive definite provided that $CC'$ is positive definite. This model explicitly allows for dynamic dependence between the volatility series. The GARCH-BEKK$(1,1)$ reduces to

$$H_t = CC' + A(\varepsilon_{t-1}\varepsilon'_{t-1})A' + BH_{t-1}B'. \tag{16}$$

with

$$A = \begin{bmatrix} \alpha_{11} & \alpha_{12} \\ \alpha_{21} & \alpha_{22} \end{bmatrix} \qquad \text{and} \qquad B = \begin{bmatrix} \beta_{11} & \beta_{12} \\ \beta_{21} & \beta_{22} \end{bmatrix}. \tag{17}$$

The coefficient $\alpha_{12}$ describes a cross-effect running from the lagged error of the second market to the first market's conditional variance while the coefficient $\alpha_{21}$ describes the cross-effect in the other direction. Matrix $B$ depicts the impact of the past conditional variances on the current conditional variance. That means the off diagonal elements in $B$ show to which extend the conditional variance of one market is correlated with the lagged

[10] Applying univariate GARCH models to analyze volatility transmission between markets usually takes place in a two step procedure in the first step GARCH-type models are applied to the return series and the residuals are computed. Hence, in a second step, the squared residuals of one estimated model is used as regressor in the variance equation of the other series. Using the two step methodology is inferior to the use of a multivariate GARCH specification due to the ability of modelling the variances being influenced by lagged covariances.

conditional variance of the other market. The matrix notation can be expanded to

$$\begin{aligned} h_{11,t} &= c_{01} + \alpha_{11}^2 \varepsilon_{1,t-1}^2 + 2\alpha_{11}\alpha_{12}\varepsilon_{1,t-1}\varepsilon_{2,t-1} + \alpha_{12}^2 \varepsilon_{2,t-1}^2 \\ &\quad + \beta_{11}^2 h_{1,t-1} + 2\beta_{11}\beta_{12} h_{12,t-1} + \beta_{12}^2 h_{22,t-1} \qquad (18) \\ h_{22,t} &= c_{02} + \alpha_{21}^2 \varepsilon_{1,t-1}^2 + 2\alpha_{21}\alpha_{22}\varepsilon_{1,t-1}\varepsilon_{2,t-1} + \alpha_{22}^2 \varepsilon_{2,t-1}^2 \\ &\quad + \beta_{21}^2 h_{1,t-1} + 2\beta_{21}\beta_{22} h_{12,t-1} + \beta_{22}^2 h_{22,t-1} \qquad (19) \end{aligned}$$

The advantage of the BEKK formulation is the relatively small number of parameters that have to be estimated. In the bivariate case there are 11 parameters to be estimated. Furthermore it allows the covariances to be influenced by lagged variances. To investigate the volatility transmission mechanisms, we apply the two-step sequential estimation strategy. In the first step we model the conditional mean equation using the VECM described in the previous section. For the second estimation step, we take the residual vector $\varepsilon_t$ of the estimated VECM and estimate the conditional covariance matrix using quasi maximum likelihood (QML) estimation as proposed by Bollesrlev and Wooldridge (1992). The QML estimators applied to GARCH models are consistent even if the true distribution is non-Gaussian. Tse (1999) showed the asymptotic equivalence of the two-step estimation procedures to the joint estimation of the VECM and GARCH model, due to the OLS estimator being unbiased and consistent even if heteroscedasticity is present.

Let the first equation of the BEKK-GARCH model represent the futures market while the second equation of the model stands for the spot market. To investigate the existence of volatility spillovers from the spot market to the futures market we have to test the joint hypothesis

$$H_0 : \alpha_{12} = 0 \cap \beta_{12} = 0 \text{ against the alternative } H_1 : \alpha_{12} \neq 0 \text{ or } \beta_{12} \neq 0. \qquad (20)$$

For to check if there is a volatility transmission from the futures to the spot market we have to test the joint hypothesis

$$H_0 : \alpha_{21} = 0 \cap \beta_{21} = 0 \text{ against the alternative } H_1 : \alpha_{21} \neq 0 \text{ or } \beta_{21} \neq 0. \qquad (21)$$

In the case the null hypothesis holds there are no volatility spillovers from the corresponding market to the other one.

# 5 Empirical Results

A first visual inspection of the spot and futures market data was given in Section 3. In this section we provide a more detailed analysis of the relationship between the theoretically derived and the observed futures price series' simultaneous evolution based on the methods introduced in Section 4. First we show the summary statistics. We restrict the analysis to the contracts with maturity in December 2008 and December 2009, respectively. We show the statistics for daily data as well as for high frequency data based at the frequencies $h = 10$ and 30 minutes.[11] The results are depicted in Table 1 whereas Panel A shows the descriptive statistics of the contract with maturity in December 2008 and Panel B shows the descriptive statistics of the contract with maturity in December 2009, respectively.

Table 1: Descriptive Statistics

| Panel A - Contract with maturity in December 2008 | | | | | | |
|---|---|---|---|---|---|---|
| Series | # obs. | Mean | Stand. Dev. | Skewness | Kurtosis | Jarque-Bera |
| $\Delta P_t^{TF}(10)$ | 7007 | -0.0001 | 0.001 | -1.983 | 101.197 | $> 1000$ [0.00] |
| $\Delta P_t^{F}(10)$ | 7007 | -0.0002 | 0.001 | -1.200 | 84.434 | $> 1000$ [0.00] |
| $\Delta P_t^{TF}(30)$ | 2335 | -0.0002 | 0.014 | -0.841 | 29.046 | $> 1000$ [0.00] |
| $\Delta P_t^{F}(30)$ | 2335 | -0.0002 | 0.011 | -0.604 | 26.754 | $> 1000$ [0.00] |
| $\Delta P_t^{TF}(d)$ | 159 | -0.0003 | 0.031 | -0.792 | 4.427 | 30.123 [0.00] |
| $\Delta P_t^{F}(d)$ | 159 | -0.0004 | 0.032 | -0.630 | 3.752 | 14.275 [0.00] |
| **Panel B - Contract with maturity in December 2009** | | | | | | |
| Series | # obs. | Mean | Stand. Dev. | Skewness | Kurtosis | Jarque-Bera |
| $\Delta P_t^{TF}(10)$ | 9791 | -0.0002 | 0.011 | 1.377 | 71.459 | $> 1000$ [0.00] |
| $\Delta P_t^{F}(10)$ | 9791 | -0.0002 | 0.012 | 1.168 | 70.389 | $> 1000$ [0.00] |
| $\Delta P_t^{TF}(30)$ | 3263 | -0.0003 | 0.014 | 0.377 | 19.616 | $> 1000$ [0.00] |
| $\Delta P_t^{F}(30)$ | 3263 | -0.0003 | 0.021 | 300 | 21.621 | $> 1000$ [0.00] |
| $\Delta P_t^{TF}(d)$ | 284 | -0.0004 | 0.033 | -0.071 | 3.866 | 9.113 [0.01] |
| $\Delta P_t^{F}(d)$ | 284 | -0.0004 | 0.032 | 0.081 | 4.311 | 20.665 [0.00] |

**Notes:** $p$-values in brackets.

Within the analysis of the contract with maturity in December 2008, Phase II covers 160 days with observed transactions in both markets yielding 2336 and 7008 equidistant

[11]Besides the frequencies of 10 and 30 minutes we estimated the model on other intraday frequencies as well. Here, the results have been similar to those reported.

high-frequency observations at frequency $h = 10$ and 30 minutes, respectively.[12] Based on the high frequency log-prices we compute the log-return series of both markets. Table 1 shows the descriptive statistics of the log-return series based on 10 and 30 minute high-frequency data as well as based on daily data. The means of the log returns are negative but very close to zero at each frequency and for each of the contracts; the standard deviation increases with decreasing frequencies. The summary statistics give evidence that the log-return distribution is slightly left-skewed at most of the analyzed frequencies for both contracts. Negative skewness in combination with strong excess kurtosis clearly leads to the rejection of the null-hypothesis of normally-distributed log returns at least at the one percent level at each of the analyzed frequencies which is confirmed by the Jarque-Bera-statistic. Besides the analysis presented in Table 1, we analyze the futures contract with maturity in December 2009 and the corresponding theoretically derived futures, whereas we only account for the post 15/12/08 period. This is justified by the fact that the transaction volume of the futures with maturity in December 2009 in the post 15/12/08 period lies considerably above the futures' transaction volume in the pre 15/12/08 period since the highest proportion of futures trading within the pre 15/12/08 period takes place in the futures with maturity in December 2008. The results of Table 2

Table 2: Descriptive Statistics

| Contract with maturity in December 2009 - post 15/12/08 period | | | | | | |
|---|---|---|---|---|---|---|
| Series | # obs. | Mean | Stand. Dev. | Skewness | Kurtosis | Jarque-Bera |
| $\Delta P_t^{TF}(10)$ | 2976 | -0.0001 | 0.010 | 2.363 | 41.642 | $> 1000$ [0.00] |
| $\Delta P_t^{F}(10)$ | 2976 | -0.0001 | 0.006 | 1.808 | 35.791 | $> 1000$ [0.00] |
| $\Delta P_t^{TF}(30)$ | 992 | -0.0002 | 0.012 | 0.870 | 11.257 | $> 1000$ [0.00] |
| $\Delta P_t^{F}(30)$ | 992 | -0.0002 | 0.011 | 0.620 | 11.205 | $> 1000$ [0.00] |
| $\Delta P_t^{TF}(d)$ | 100 | -0.0010 | 0.043 | 0.208 | 2.732 | 1.021 [0.60] |
| $\Delta P_t^{F}(d)$ | 100 | -0.0009 | 0.041 | 0.324 | 3.174 | 1.871 [0.39] |

**Notes:** $p$-values in brackets.

[12]Note that there are 14 additional days within the daily sample of the contract with maturity in December 2008. These days are not accounted for within the high-frequency analysis since no data of at least one of both exchanges concerning the according trading days has been available. Concerning the December 2009 contract the daily data base covers transaction up to 19/05/2009. High-frequency data is restricted to the period outlined in section 3.

are similar to those of Table 1. Again the hypothesis of normally distributed log returns has to be rejected for all intraday frequencies. This does not hold for the distribution of the daily data. Here the Jarque-Bera statistic gives evidence that the hypothesis of normally distributed log returns cannot be rejected for any market. In line with the results of Table 1, Table 2 shows that the means of the theoretically derived futures and those of the empirically observed futures are negative but very close to zero and the standard deviation increases with decreasing frequency.

In a next step we check the stationarity of the series described above. Therefore we apply the both most commonly used unit root tests. With the ADF test we test the hypothesis that the series has a unit root, that means the series is nonstationary. Rejecting the hypothesis gives evidence of a stationary series. Applying the KPSS test, we test the hypothesis of the series having no unit root, that means we test for stationarity. The results of the unit root tests are summarized in Table 3. Besides the series in levels, we apply the tests to the first differences of the series. Concerning the series in levels, we account for a trend and a constant. Concerning the series in first differences, we do not account for a trend. The number of lags in the test is chosen by the Schwarz information criterion. The results of Table 3 clearly indicate the existence of a unit root in the levels series. On the other hand, Table 3 indicates that there is no unit root in the first differences. Together, both results show that the theoretically derived as well as the observed futures series are integrated of order one. Having shown that the series of both assets are integrated of order one, the appropriate model to investigate the price transmission mechanisms is a vector error correction model. The optimal lag order is determined by the Schwarz information criterion.

Table 4 shows the long run relationship between the spot and the futures series derived from the vector error corretion model. Within the VECM, we check whether the error term $p^{TF}_{t-1} - p^{F}_{t-1}$ of period $t-1$ enters significantly into the equation of the spot and/or futures price. Panel A shows that the error of the previous period enters highly significant into both equations regarding the futures series with maturity in December 2008 and the corresponding spot series at both analyzed intraday frequencies. The error $p^{TF}_{t-1} - p^{F}_{t-1}$ enters the futures equation at each frequency at the one percent level. Regarding the spot market, statistical significance on the one percent level is observed for the frequencies 10 and 30 minutes as well. Furthermore, at each analyzed intraday frequency the sign of both estimated coefficients is the expected one. Spot prices exceeding futures prices in period $t-1$ lead to increasing futures prices and decreasing spot prices, which is exactly what we would expect in the presence of a disequilibrium. Except at the 10 minute frequency the futures price reaction is stronger than the spot price reaction, whereas the proportion of

Table 3: Unitroot tests for levels and differences

| | ADF test | | KPSS test | |
|---|---|---|---|---|
| | levels | differences | levels | differences |
| Panel A - Contract with maturity in December 2008 | | | | |
| $P_t^{TF}(10)$ | −2.129 | −55.317*** | 1.760*** | 0.370* |
| $P_t^{F}(10)$ | −2.250 | −82.403*** | 1.790*** | 0.393* |
| $P_t^{TF}(30)$ | −2.152 | −45.166*** | 0.989*** | 0.333 |
| $P_t^{F}(30)$ | −2.257 | −46.800*** | 1.004*** | 0.360* |
| $P_t^{TF}(d)$ | −2.242 | −12.157*** | 0.281*** | 0.313 |
| $P_t^{F}(d)$ | −2.048 | −11.706*** | 0.282*** | 0.290 |
| Panel B - Contract with maturity in December 2009 | | | | |
| $P_t^{TF}(10)$ | −2.426 | −93.806*** | 1.612*** | 0.182 |
| $P_t^{F}(10)$ | −2.408 | −98.163*** | 1.7508*** | 0.225 |
| $P_t^{TF}(30)$ | −2.465 | −53.678*** | 0.964*** | 0.188 |
| $P_t^{F}(30)$ | −2.397 | −55.807*** | 1.046*** | 0.208 |
| $P_t^{TF}(d)$ | −1.547 | −13.230*** | 0.210** | 0.178 |
| $P_t^{F}(d)$ | −1.522 | −13.045*** | 0.216*** | 0.182 |
| Panel C - Contract with maturity in December 2009 post 15/12/08 period | | | | |
| $P_t^{TF}(10)$ | −0.640 | −52.075*** | 1.339*** | 0.346* |
| $P_t^{F}(10)$ | −0.586 | −55.409*** | 1.342*** | 0.339* |
| $P_t^{TF}(30)$ | −0.631 | −29.715*** | 0.803*** | 0.350* |
| $P_t^{F}(30)$ | −0.522 | −31.447*** | 0.804*** | 0.402* |
| $P_t^{TF}(d)$ | −1.479 | −8.265*** | 0.261*** | 0.338 |
| $P_t^{F}(d)$ | −1.484 | −8.033*** | 0.260*** | 0.343 |

**Notes:** $\star$, $\star\star$, and $\star\star\star$ indicate statistical significance at the 10, 5, and 1 percent level.

the error that is worked off within the following period declines with increasing frequency from 0.063 to 0.032 within the futures market. Neither a long-run price leader nor a long run price taker can be identified within the early stage of Phase II. On the basis of the high-frequency data there is a contrast in long run price discovery between the contract with maturity in December 2008 and the contract with maturity in December 2009 shown in Panel B of Table 4. Regarding the contract with maturity in December 2009 the error $p_{t-1}^{TF} - p_{t-1}^{F}$ enters the futures equation at each frequency at least at the one percent level concerning the full period sample. Contrary, the error term significantly enters the spot equation at the 10 minute frequency but not at the 30 minute frequency. The proportion of the error that is worked off in the futures market within the following period exceeds the proportion of the error that is worked off in the spot market. Hence, the spot market seems to act as price leading market. Again, the signs of the estimated coefficients of the error terms are the expected ones. On the basis of the post 15/12/08 period a different situation can be observed. The error term enters the spot market equation significantly at both frequencies at the one percent level. The proportion of the error that is worked off within the following period in the spot market strongly exceeds the ones reported in Panels A and B. On the other hand the error term significantly enters the 10 minute frequency futures equation at the five percent level but it does not enter the 30 minute frequency futures equation. The speed of adjustment in the spot market is about three times as high as the one in the futures market whereas the signs of the estimated coefficients of the error terms again are the expected ones. Hence, there is strong evidence that the futures market is the price leading market. The oppositional results of Panel B can be attributed to the low transaction volume of the futures contract with maturity in December 2009 within the pre 15/12/08 period.

The situation is different regarding daily data. Having observed a spot price overneath the futures price, one would expect the spot price to fall and/or the futures price to raise. Actually, on the basis of the contract with maturity in December 2008 the spot price as well as the futures price react positive to deviations from the equilibrium path whereas the futures price reaction overcompensates the spot price reaction. Regarding daily data concerning the contract with maturity in December 2009 the previous period's error does neither enter the spot, $p$-value $= 0.58$, nor the futures equation, $p$-value $= 0.30$, which is in sharp contrast to the daily data presented in Panel A. This result is confirmed for the post 15/12/08 period depicted in Panel C. Again the error of the previous period does neither enter the spot nor the futures equation with $p$-values of 0.22 and 0.68.[13] Therefore an intraday analysis seems to be indispensable.

Besides the reported results concerning the adjustment coefficients, the estimated cointegration vectors are highly significant and justify the choice of the prespecified coin-

[13]We assign the abscence of a statistically significant long run relationship to the small number of observations. Concerning two lags in the cointegration relationship indicates statistical significance of the error term of both markets on the one percent level in each panel except for the coefficent in the spot equation of Panel C that is significant on the ten percent level. These results clearly indicate the existence of a statistically significant long run relationship. In each case the estimated coefficient of the spot equation clearly lies above the estimated one of the futures equation. This again gives evidence that the spot reacts stronger to unequal prices of the previous period. Hence, in the terms of the price discovery literature this indicates that information is reflected faster in the futures than in the spot market.

tegrating vector $\beta = (1\ -1)'$ since at each frequency a 95 percent confidence interval for the cointegrating vector contains the prespecified cointegrating vector. For the computation of the long run price discovery measures below we use the restricted cointegration vector $\beta = (1\ -1)'$, for further computations we use the residuals of the models with estimated cointegration vectors $\hat{\beta}$.[14]

Table 4: Long run Relationship I - VECM

| | adjustment vector | | cointegrating vector | |
|---|---|---|---|---|
| frequency | $\alpha^{TF}$ | $\alpha^{F}$ | $\beta^{TF}$ | $\beta^{F}$ |
| Panel A - Contract with maturity in December 2008 | | | | |
| 10 | $-0.045^{***}$ (0.005) | $0.032^{***}$ (0.006) | 1 (−) | −1.00 (0.000) |
| 30 | $-0.049^{***}$ (0.017) | $0.063^{***}$ (0.019) | 1 (−) | −1.00 (0.00) |
| daily | $0.547^{*}$ (0.300) | $0.677^{**}$ (0.296) | 1 (−) | −1.00 (0.000) |
| Panel B - Contract with maturity in December 2009 full period | | | | |
| 10 | $-0.008^{***}$ (0.003) | $0.009^{***}$ (0.003) | 1 (−) | −1.00 (0.000) |
| 30 | −0.005 (0.008) | $0.019^{**}$ (0.008) | 1 (−) | −1.00 (0.001) |
| daily | 0.059 (0.097) | 0.098 (0.095) | 1 (−) | −1.00 (0.003) |
| Panel C - Contract with maturity in December 2009 post 15/12/08 period | | | | |
| 10 | $-0.144^{***}$ (0.017) | $0.043^{**}$ (0.018) | 1 (−) | −1.00 (0.000) |
| 30 | $-0.234^{***}$ (0.056) | 0.088 (0.054) | 1 (−) | −1.00 (0.000) |
| daily | −0.685 (0.563) | −0.238 (0.570) | 1 (−) | −1.00 (0.001) |

**Notes:** Standard errors in parenthesis.

Table 5 summarizes the price discovery measures based on the estimated adjustment coefficients $\hat{\alpha}$ and the prespecified cointegrating vector $\beta = (1\ -1)'$ interpreted above. Note that we abdicate to report the values of the price discovery measures when the error term does not enter the equation of at least one series. Panel A of Table 5 gives evidence that the price discovery process concerning the contract with maturity in December 2008 takes place within both markets based on the common factor weights as well as based on the information shares. The proportion the futures market contributes to the long run

[14]No different results could be observed by estimating the models on the basis of the VECM with restricted cointegrating vector $\beta = (1\ -1)'$.

price discovery process increases from 0.464 to 0.585 as the frequency increases from 30 to 10 minutes. This is confirmed by the information share of the futures market that increases from 0.520 to 0.647 whereas the ranges of the spot market's and the futures market's information share are not disjoint. The results are in line with those reported in Table 4 and confirm that no market can be identified as predominant long run price leader. Panels B and C refer to the futures price with maturity in December 2009 and the corresponding spot price. Again, the results differ to high degree depending on the period that is analyzed. Concerning the full period the spot market's common factor weights are 0.530 and 0.792 for the frequency of 10 and 30 minutes, respectively. Hence, the spot market seems to be the price leading market at the lower frequency of 30 minutes whereas both markets contribute to the price discovery process at the higher frequency of 10 minutes. This is confirmed by the futures market's information shares of 0.349 and 0.478 for the frequency of 30 and 10 minutes, respectively. Again, the ranges of the futures market's information shares are not disjoint. Concerning the post 15/12/08 period the situation has changed. At both frequencies the futures market's common factor weights (0.726 and 0.770) are about three times as high as the spot market's ones. The price leadership of the futures market implyed by the common factor weights are confirmed by the futures market's information shares exceeding one half. However, the ranges of the information shares again are not disjoint. Hence, the results are partly in line with the ones of Table 4.

Both, Table 4 and Table 5 as well, strongly support the conclusion that the long run price discovery process takes place within both markets concerning the futures contract with maturity in December 2008, whereas at least at the higher frequency of 10 minutes the futures market's relevance in the long run price discovery process exceeds the spot market one's. Concerning the contract with maturity in December 2009 the results storngly depend on the analyzed sample. Analyzing the full sample leads to the conclusion that the long run price discovery process predominantly takes place within the spot market which can be attributed to the low transaction volume of the futures with maturity in December 2009 in the pre 15/12/08 period. Looking at the post 15/12/08 period the results give evidence for a starched impact of the futures contract on the long run price discovery process.

Table 6 addresses the question of the short run dynamics in carbon spot and futures markets. The results of Panel A show that on the basis of the daily data for the futures contract with maturity in December 2008 no series is identified to lead the other one in the short run context, which is confirmed by the the $p$-values of 0.33 and 0.32, respectively. The situation is different for the contract with maturity in December 2009 regarding the

Table 5: Long run Relationship II - Price Discovery

| | CFW | | IS for futures | |
|---|---|---|---|---|
| | futures | spot | mean | range |
| Panel A - Contract with maturity in December 2008 | | | | |
| 10 | 0.585 | 0.415 | 0.647 | 0.358 |
| 30 | 0.464 | 0.536 | 0.520 | 0.615 |
| daily | 0.447 | 0.553 | 0.400 | 0.100 |
| Panel B - Contract with maturity in December 2009 full period | | | | |
| 10 | 0.470 | 0.530 | 0.478 | 0.490 |
| 30 | 0.208 | 0.792 | 0.349 | 0.664 |
| daily | - | - | - | - |
| Panel C - Contract with maturity in December 2009 post 15/12/08 period | | | | |
| 10 | 0.770 | 0.230 | 0.689 | 0.564 |
| 30 | 0.726 | 0.274 | 0.556 | 0.847 |
| daily | - | - | - | - |

period from 01/05/08 to 18/03/09. There is evidence that the futures leads the spot since the hypothesis that the futures does not Granger cause the spot has to be rejected at the five percent significance level regarding the full period and at the ten percent level regarding the post 15/12/08 period. Contrary the hypothesis that the spot does not Granger cause the futures cannot be rejected at any reasonable significance level. Now we will have a closer look at the high frequency data. First we consider the situation of the futures contract with maturity in December 2008. At both of the analyzed frequencies the results clearly imply that the hypothesis that the futures market series does not Granger cause the spot market series has to be rejected at any significance level. Regarding the opposite hypothesis there is evidence that at the highest frequency of ten minutes the spot market series Granger causes the futures market series at the ten percent level. No Granger causality from the spot to the futures can be observed at the 30 minute frequency. The results indicate bi-directional Granger causality between the futures and the spot market, whereas Granger-causality from the futures market to the spot market can be observed at each frequency. Regarding the contract with maturity in December 2009 the results imply that in the short run there is bi-directional Granger causality between both markets. Panel B as well as Panel C show that for the full period as well as for the post 15/12/08 period the hypothesis that the futures does not Granger cause the spot has to be rejected at any significance level. On the other hand the hypothesis that the spot

Table 6: Short run Dynamics - Granger Causality

| frequency | spot does not cause futures | futures does not cause spot |
|---|---|---|
| Panel A - Contract with maturity in December 2008 | | |
| 10 | 9.311 [0.05] | 44.131 [0.00] |
| 30 | 4.060 [0.39] | 55.329 [0.00] |
| daily | 2.237 [0.33] | 2.299 [0.32] |
| Panel B - Contract with maturity in December 2009 full period | | |
| 10 | 74.546 [0.00] | 61.535 [0.00] |
| 30 | 60.148 [0.00] | 57.037 [0.00] |
| daily | 1.531 [0.47] | 6.059 [0.04] |
| Panel C - Contract with maturity in December 2009 post 15/12/08 period | | |
| 10 | 17.716 [0.00] | 36.849 [0.00] |
| 30 | 20.196 [0.00] | 19.449 [0.00] |
| daily | 0.172 [0.92] | 4.885 [0.08] |

**Notes:** $p$-values in brackets, computed by robust standard errors.

market does not Granger cause the futures market has to be rejected at any significance level as well. As a whole the results imply that there is bidirectional Granger causality between both markets. This in turn means that no market can be detected as price leader in the short run context. For none of the analyzed periods an analysis on the basis of daily data proved to be sufficient since the results of the high-frequency analysis imply a more complex causality structure.

So far we have analyzed the price transmission in the carbon spot and futures markets. Additionally, we present the volatility transmission structure in carbon spot and futures markets. This is based on the fact that the estimated residuals $\hat{\varepsilon}_t$ prove to be uncorrelated but the squared residuals $\hat{\varepsilon}_t^2$ prove to be correlated on the frequencies of 10 and 30 minutes. As a whole this provides evidence for the existence of conditional heteroscedasticity. Hence, the utilization of the multivariate BEKK-GARCH model to the residuals of the VECM clearly seems to be appropriate.

The estimation results of the GARCH-BEKK(1,1)-specification are summarized in Table 7 whereas the observed futures price series is the first equation of the model, the theoretically derived futures price series is the second equation of the model. Within the variance equation of each market we abdicate to present the estimated coefficients on the past period's squared innovations as well as the estimated coefficients on the past period's conditional variance of the according market. Here, $\alpha_{12}$ ($\alpha_{21}$) indicates to which extend the squared lagged innovation of the spot market (futures market) determines the conditional variance of the futures market (spot market). On the other hand $\beta_{12}$ ($\beta_{21}$) indicates the extend to which the lagged conditional variance of the spot market (futures market) determines the conditional variance of the futures market (spot market) within the current period.

Table 7: Coefficient Estimates GARCH BEKK Specification

| | $\alpha_{12}$ | $\alpha_{21}$ | $\beta_{12}$ | $\beta_{21}$ | $\alpha_{12} = \beta_{12} = 0$ | $\alpha_{21} = \beta_{21} = 0$ |
|---|---|---|---|---|---|---|
| Panel A - Contract with maturity in December 2008 | | | | | | |
| 10 | 0.182* | −0.681*** | 0.048 | 1.937 | 3.631 | 108.676 |
| | (0.096) | (0.157) | (0.167) | (1.569) | [0.163] | [0.000] |
| 30 | −0.810*** | −0.385*** | 0.175 | −1.318* | 14.724 | 229.844 |
| | (0.213) | (0.133) | (0.939) | (0.742) | [0.001] | [0.000] |
| daily | −0.539*** | 0.695*** | 0.009 | 0.132 | 8.584 | 5.093 |
| | (0.174) | (0.226) | (0.191) | (0.352) | [0.014] | [0.078] |
| Panel B - Contract with maturity in December 2009 | | | | | | |
| 10 | −0.559*** | 0.742*** | 1.164*** | −0.775*** | 133.432 | 86.818 |
| | (0.111) | (0.109) | (0.123) | (0.124) | [0.000] | [0.000] |
| 30 | 0.231 | 0.149 | 0.938*** | 0.546 | 16.367 | 3.532 |
| | (0.179) | (0.105) | (0.358) | (0.314) | [0.000] | [0.171] |
| daily | 0.265 | −0.819*** | 0.109 | −0.036 | 4.353 | 20.934 |
| | (0.166) | (0.282) | (0.239) | (0.307) | [0.113] | [0.000] |
| Panel C - Contract with maturity in December 2009 post 15/12/08 period | | | | | | |
| 10 | 0.308 | −0.961*** | 0.078 | −1.437 | 2.953 | 27.094 |
| | (0.287) | (0.253) | (1.005) | (1.162) | [0.228] | [0.000] |
| 30 | 0.279*** | −0.201*** | 1.799*** | −0.225*** | 40.595 | 23.234 |
| | (0.092) | (0.046) | (0.369) | (0.353) | [0.000] | [0.000] |
| daily | 0.168 | 0.170 | 8.851 | −6.896 | 1.821 | 1.463 |
| | (0.335) | (0.340) | (7.817) | (6.849) | [0.402] | [0.481] |

**Notes:** Robust standard errors in parenthesis. *p*-values in brackets.

Table 7 shows the estimated coefficients of the GARCH-BEKK specification relevant for the analysis of the volatility transmission structure in columns two to five. Numbers in parenthesis are robust standard errors. Column six (seven) shows the $\chi^2$-distributed test statistic of the null hypothesis of no volatility spillovers from the spot (futures) market to the futures (spot) market. Numbers in brackets are $p$-values. Concerning the futures contract with maturity in December 2008 there is evidence that the squared lagged errors of the futures market affect the volatility in the spot market at the 10 minute frequency due to the estimated coefficient $\hat{\alpha}_{21} = -0.681$, $(p = 0.000)$. The estimated coefficient $\hat{\alpha}_{12}$ is weakly significant. Neither the lagged variance of the spot market nor the one of the futures market enter the corresponding equation significantly. The joint hypothesis $H_0 : \alpha_{12} = \beta_{12} = 0$ cannot be rejected at any level implying that there is no volatility transmission from the spot to the futures market. Contrary, there is strong evidence of volatility spillovers into the opposite direction due to the test statistic of $\chi^2 = 108.676$, $(p = 0.000)$. On the basis of the 30-minute frequency sample the estimated coefficients of squared lagged error of both markets are highly significant. Bidirectional volatility transmission is confirmed by the test statistics of both joint hypotheses as reported in columns six and seven.

Regarding the futures contract with maturity in December 2009 the picture changes concerning the full sample. Each of the estimated coefficients is significant at the one percent level at the 10 minute frequency. Furthermore, the joint hypothesis $H_0 : \alpha_{12} = \beta_{12} = 0$ as well as the joint hypothesis $H_0 : \alpha_{21} = \beta_{21} = 0$ has to be rejected at any level. Hence, bidirectional volatility transmission is implyed. On the basis of the 30-minute frequency sample only the estimated coefficient $\hat{\beta}_{12}$ of the lagged spot market variance enters the futures equation highly significant. This is confirmed by the test statistic of $\chi^2 = 3.532$, $(p = 0.171)$, concerning the hypothesis of no volatility transmission from the futures market to the spot market, and the test statistic of $\chi^2 = 16.367$, $(p = 0.000)$, concerning the hypothesis of no volatility transmission from the spot market to the futures market.

Concerning the futures contract with maturity in December 2009 restricted to the post 15/12/08 period the results are very similar to the ones reported in Panel A. Volatilty transmission from the futures market to the spot market at the frequency of 10 minutes is implyed by the test statistic of $\chi^2 = 27.094$, $(p = 0.000)$, concerning the hypothesis $H_0 : \alpha_{21} = \beta_{21} = 0$. Contrary, no transmission of volatility can be observed into the other direction due to the test statistic of $\chi^2 = 2.953$, $(p = 0.228)$. Again, the spot market's volatility is exclusively affected by the squared lagged errors of the futures market. Neither the lagged variance of the spot market nor the one of the futures market enter the corresponding equation significantly. At the 30 minute frequency the results of Panel C again are very similar to those of Panel A. Both joint hypotheses $H_0 : \alpha_{12} = \beta_{12} = 0$ as well as $H_0 : \alpha_{21} = \beta_{21} = 0$ have to be rejected at any reasonable level, implying bidirectional volatility transmission. Contrary to Panel A, each of the estimated coefficients is significant at the one percent level.

Again, the contrarian results of Panel B can be attributed to the low transaction volume of the futures with maturity in December 2009 in the pre 15/12/08 period. As already reported for the structure of the price discovery process the causality structure in the second conditional moment is to complex to be captured by an analysis of daily data.

# 6 Conclusion

The paper addresses the question of causality in the first and the second conditional moments of the carbon futures and spot market prices in Phase II of the EU ETS. The analysis was split up in a daily and a high frequency perspective based on spot market data of the BlueNext, Paris, and futures market data of the European Climate Exchange, London. Concerning causality within the first conditional moment we separate the analysis into a long run relationship price discovery analysis and a short run dynamics causality analysis. We estimate a vector error correction model of the spot and futures price series and compute the common factor weights proposed by Schwarz and Szakmary (1994) and the information share proposed by Hasbrouck (1995), both based on the estimated coefficients of the error term. To discover the short run dynamics causality structure we perform Granger causality tests proposed by Granger (1969). In a second step we use the residuals of the vector error correction model to estimate a multivariate GARCH-BEKK model of Engle and Kroner (1995) yielding the possibility to check the volatility transmission structure between the spot and the futures market.

Regarding the price transmission process our results suggest that in a long run context no market can clearly be identified as price leader concerning the futures contract with maturity in December 2008 whereas the futures market's contribution to the long run price discovery process increases with increasing frequency. Both, the spot and the futures prices react on divergences from the long run equilibrium to a similar extend. This holds on a daily perspective as well as on a high frequency perspective. Regarding the futures contract with maturity in December 2009, the results strongly depend on the time period of the analyzed data sample. At the basis of the sample containing observations from 01/05/08 to 18/03/09 the results imply that the long run price discovery process predominantly takes place within the spot market, at least at the frequency of 30 minutes. This has to be attributed to the low transaction volume of the futures contract with maturity in December 2009 within the pre 15/12/08 period. Restricting the analyzed sample to the post 15/12/08 period the results clearly give evidence that the long run price discovery process predominantly takes place in the futures market. Furthermore, the speed of adjustment in the case of disequilibria has strongly increased relative to the early stage of Phase II. Hence, the results imply that the futures market's relevance in the long run price discovery process is higher in the more mature stage of Phase II. Contrary, on the basis of daily data no significant reactions in the case of disequilibria are observed at all.

Concerning the short run dynamics we are confronted with a different situation. Regarding the futures contract with maturity in December 2008 no Granger causality can be detected on a daily basis. At the intraday perspective bidirectional Granger causality is implied by our analysis whereas causality of the futures market seems to be stronger. Regarding the futures contract with maturity in December 2009, the daily data gives evidence that the futures market does Granger cause the spot market, but the spot market does not Granger cause the futures market. Contrary to the unidirectioal Granger causality observed on the basis of daily data, bidirectional Granger causality is detected on the basis of high-frequency data concerning each of the analyzed frequencies. Hence, the results do not identify a unique short run dynamics price leader.

Additionally to the short run dynamics and the long run price discovery process the paper contains an analysis of volatility transmission. Regarding the futures contract with maturity in December 2008 there is evidence of predominant volatility spillovers from the futures to the spot market concerning the high frequency perspective. In the corresponding daily analysis the results implicate bi-directional volatility spillovers. Again, we observe a different structure of volatility transmission concerning the futures with maturity in December 2009 covering transactions of the perid 01/05/08 to 18/03/09. Restricting the sample to the post 15/12/08 period yields results that are very similar to those of the futures contract with maturity in December 2008.

The central results of the paper can be summed up in two issues. First, we show that the causality structure in the first and second conditional moments changes as the spot and the futures market become more mature within Phase II of the EU-ETS, whereas the portion of price and volatility transmission from the futures to the spot market increases over time. Second, we show that the analysis of short run dynamics and long run price discovery as well as the analysis of the volatility transmission structure has to be augmented to a high-frequency level. The results of our study show that the analysis of daily (or even weekly) data is not sufficient to capture the causality structure in the conditional mean and the conditional variance in the European carbon markets.

# References


[1] Alberola, E. and Chevallier, J. 2009a. European carbon prices and banking restrictions: Evidence from Phase I (2005-2007). Energy Journal **30(3)**: 51-80.

[2] Alberola, E. and Chevallier, J. 2009b. Banking and borrowing in the EU ETS: An econometric appraisal of the 2005-2007 intertemporal market. International Journal of Energy, Environment and Economics: forthcoming.

[3] Alberola, E., Chevallier, J. and Cheze, B. 2008. Price drivers and structural breaks in European carbon prices 2005-07. Energy Policy **36(2)**: 787-797.

[4] Alberola, E., Chevallier, J. and Cheze, B. 2009. The EU Emissions Trading Scheme: Disentangling the effects of of industrial production and CO2 emissions on European carbon prices. International Economics **116**, 95-128.

[5] Benz, E. and Hengelbrock, J. 2008. Price discovery and liquidity in the European CO2 futures market. Working Paper. Bonn Graduate School of Economics.

[6] Benz, E. and Truck, S. 2006a. CO2 emission allowances trading in Europe - Spezifying a new class of assets. Problems and Perspectives in Management **4**.

[7] Benz, E. and Truck, S. 2009. Modeling the price dynamics of $CO_2$ emission allowances. Energy Economics **31(1)**: 4-15.

[8] Boeringer, C., Hoffmann, T., Lange, A., Loschel, A. and Moslener, U. 2005. Assesing emissions regulation in Europe: An interactive simulation approach. The Energy Journal **26 (4)**: 1-22.

[9] Bollerslev, T. 1986. Generalized autoregressive conditional heteroskedasticity. Journal of Econometrics **31**: 307-327.

[10] Bollerslev, T., Engle, R. and Wooldridge, J. 1988. A capital asset pricing model with time-varying covariances. Journal of Political Economy **96 (1)**: 116-131.

[11] Bollerslev, T. and Wooldridge, J. 1992. Quasi-maximum likelihood estimation and inference in dynamic models with time-varying covariances. Econometric Reviews **11**: 143-172.

[12] Borak, S., Hardle, W., Truck, S. and Werom, R. 2006. Convenience yields for $CO_2$ emission allowance futures contracts. SFB 649 Discussion Paper 2006-076. Humbolt University of Berlin.

[13] Brennan, M. 1991. The price of convenience and the valuation of commodity contingent claims. In D. Lund and B. Oksendahl (eds). Stochastic models and option values, applications to resources, environment and investment problems: 33-71.

[14] Chevallier, J. and Sevi, B. 2009. On the realized volatility of the ECX CO2 emissions 2008 futures contract: Distribution, dynamics and forecasting. Working paper, Universte Paris X Nanterre.

[15] Christiansen, A. C. and Arvanitakis, A. 2004. What determines the price of carbon in the European Union? Working Paper. European Climate Exchange.

[16] Conrad, C., Rittler, D. and Rotfuß, W. 2009. Modeling and Explaining the Movements in European Union Allowance Prices: A High-Frequency Perspective. Working Paper University Heidelberg.

[17] Cramton, P. and Kerr, S. 2002. Tradable carbon permit auctions: How and why to auction, not grandfather. Energy Policy **30 (4)**: 333-345.

[18] Daskalakis, G. and Markellos, R. N. 2006. Are the European carbon markets efficiet? Working Paper. Athens University of Economics and Business.

[19] Daskalakis, G., Psychoyios, D. and Markellos, R. N. 2006. Modeling CO2 emission allowance prices and derivatives: Evidence from the European markets. Working Paper. Athens University of Economics and Business.

[20] Engle, R. 1982. Autoregressive conditional heteroscedasticity with estimates of the variance of United Kingdom inflation. Econometrica **50**: 987-1007.

[21] Engle, R. and Granger, C. 1987. Co-integration and error correction: Representation, estimation and testing. Econometrica **55 (2)**: 251-276.

[22] Engle, R. and Kroner, K. 1995. Multivariate simultaneous Generalised ARCH. Econometric Theory **11**: 122-150.

[23] European Parliament and Council 2003. Directive 2003/87/EC of the European Parliament and Council of 13 October 2003. Official Journal of the European Union, L 275, 32-46.

[24] European Parliament and Council 2004. Directive 2004/101/EC of the European Parliament and Council of 27 October 2004. Official Journal of the European Union, L 338, 18-30.

[25] European Parliament and Council 2008, Directive of the European Parliament and of the Council amending Directive 2003/87/EC so as to improve and extend the greenhouse gas emission allowance trading system of the Community.

[26] Fama, E. 1970. Efficient capital markets: A review of theory and empirical work. Journal of Finance **25 (2)**: 383-417.

[27] Fama, E. and French, K. 1987. Commodity futures prices: Some evidence on forecast power. Journal of Business **60 (1)**: 55-73.

[28] Farrimond, J. 2008. Analysis of activity in the energy markets 2008. FSA.

[29] Geman, H. 2005. Commodities and Commodity Derivatives. Chichester. John Wiley & Sons.

[30] Granger, C. 1969. Investigating causal relations by econometric models and cross-spectral methods. Econometrica **37**: 424-438.

[31] Hasbrouck, J. 1995. One security, many markets: determining the contributions to price price discovery. Journal of Finance **50**: 1175-1199.

[32] Kosobud, R. F., Stokes, H. H., Tallarico, C. D. and Scott, B. L. 2005. Valuing tradable private rights to pollute the public's air. Review of Accounting and Finance **4**: 50-78.

[33] Kruger, J. A. and Pizer, W. A. 2004. Greenhouse gas trading in Europe. The new grand policy experiment. Environment **46**: 8-23.

[34] Mansanet-Bataller, M. and Pardo, T. 2007. The effects of National Allocation Plans on carbon markets. Working Paper. Faculty of Economics, University of Valencia.

[35] Mansanet-Bataller, M., Pardo T. and Valor, E. 2007. CO2 prices, energy and weather. Energy Journal **28 (3)**: 73-92.

[36] Milunovich, G. and Joyeux, R. 2007. Market efficiency and price discovery in the EU Carbon Futures. Working Paper. Department of Economics, Macquarie University.

[37] Oberndorfer, U. and Rennings, K. 2006. The impacts of the European Union Emission Trading Scheme on competitiveness in Europe. ZEW Discussion Paper No. 06-51, Mannheim.

[38] Paolella, M. and Taschini, L. 2006. An econometric analysis of emission trading allowances. Research Paper Series No 06-26. Swiss Finance Institut.

[39] PointCarbon 2008, Carbon 2008, Post-2012 is now. Point Carbon's 5th annual conference: Carbon Market Insights 2008, Copenhagen.

[40] Rotfuß, W. 2009. Intraday price formation and volatility in the European Emissions Trading Scheme: A first analysis. ZEW Discussion Paper 09-045, Mannheim.

[41] Schwarz, T. and Szakmary, A. 1994. Price discovery in petroleum markets: arbitrage, cointegration and the time interval of analysis. Journal of Futures Markets **14**: 147-167.

[42] Seifert, J., Uhrig-Homburg, M. and Wagner, M. 2007. Dynamic Behaviour of $CO_2$ spot prices - Theory and empirical evidence. Working Paper. University of Karlsruhe.

[43] Stock, J. and Watson, M. 1988. Testing for common trends. Journal of the American Statistical Association **83**: 1097-1107.

[44] Theissen, E. 2002. Price discovery in floor and screen trading systems. Journal of Empirical Finance **9**: 455-474.

[45] Tse, Y. 1999. Price discovery and volatility spillovers in the DJIA Index and Futures markets. Journal of Futures Markets **19 (8)**: 911-930.

[46] Uhrig-Homburg, M. and Wagner, M. 2006. Success chances and optimal design of derivatives on CO2 emission certificates. Working Paper. University of Karlsruhe.

[47] Uhrig-Homburg, M. and Wagner, M. 2007. Futures price dynamics of $CO_2$ emission cetrificates - An empirical analysis. Working Paper. University of Karlsruhe.

[48] United Nations 1998. Kyoto Protocol to the United Nations Framework Convention on Climate Change. Kyoto.