HSC Research Report

HSC/12/02

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The Relationship between Spot and Futures CO_2 Emission Allowance Prices in the EU-ETS☆

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Abstract

In this paper we investigate the relationship between spot and futures prices within the EU-wide CO_2 emissions trading scheme (EU-ETS). We conduct an empirical study on price behavior, volatility term structure and correlations in different CO_2 EU Allowance (EUA) contracts during the pilot trading and Kyoto commitment periods. We find that while for the pilot trading period (2005-2007) the market was initially in backwardation, after the news of overallocation, both allowance prices and convenience yield approached zero. During the Kyoto commitment period (2008-2012), the market has changed from initial backwardation to contango with significant convenience yields in futures contracts. We further examine the dynamic structure of the relationship between spot and futures prices in the functional form by applying a new approach of dynamic semiparametric factor models (DSFM). Interestingly, our DSFM results can be related to the classic Gibson-Schwartz two-factor model for pricing contingent claims in commodity markets that uses the spot price and the instantaneous convenience yield as factors. Our results might point towards future applications of the Gibson-Schwartz model for pricing of intra- and inter-period EUA derivatives contracts.

Keywords: CO_2 Emission Trading, Commodity Markets, Spot and Futures Prices, Convenience Yields, Dynamic Semiparametric Factor Model (DSFM), Gibson-Schwartz model.
JEL: C14, G13, Q28

1. Introduction

In January 2005 the advent of the EU-wide emissions trading scheme (EU-ETS) introduced emission allowances as a new class of financial assets. Since environmental policy has historically been a command-and-control type regulation where companies had to strictly comply with

☆This research was supported by Australian Research Council through grant no. DP1096326, Deutsche Forschungsgemeinschaft through the SFB 649 'Economic Risk' and National Science Centre (NCN) through grant no. 2011/01/B/HS4/01077.

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emission standards, the new trading system represents a shift in paradigms. The new market not only requires regulated emitters to run an adequate risk management, it also provides new business development opportunities for market intermediaries and service providers like brokers or marketeers.

Under the Kyoto Protocol the EU has committed to reducing greenhouse gas (GHG) emissions by 8% compared to the 1990 level by the year 2012. All combustion installations exceeding 20 MW are affected by the trading scheme including different kinds of industries like metal, cement, paper, glass, etc., as well as refineries or coke ovens. In total, the EU-ETS includes some 12,700 installations, representing approximately 45% of EU's CO_2 emissions and comprises the world's largest GHG emissions trading system. Each participating country proposes a so-called National Allocation Plan (NAP) including caps on greenhouse gas emissions for power plants and other large point sources which must subsequently be approved by the European Commission. After an initial pilot trading period (2005-2007), in 2008 there were new allocation plans for each of the countries and the first Kyoto commitment trading period will last until 2012. From 2013 on, again after new allocation of allowances, the third trading period will commence and last until 2020.

Failure to submit a sufficient amount of allowances resulted in sanction payments of 40 EUR per missing ton of CO_2 allowances during the pilot period and 100 EUR in the Kyoto commitment period. Hence, the new market forces companies to hold an adequate number of allowances according to their carbon dioxide output. As a consequence, participating companies face several risks specific to emissions trading. In particular, price risk (of fluctuating allowance prices) and volume risk (due to unexpected fluctuations in energy demand the emitters do not know ex ante their exact demand for EUAs) have to be considered. Naturally, market generic risks – like counterparty, operational, reputational, etc. – are also present. Participating companies will have to develop adequate risk management strategies as well as reliable models for the demand and for CO_2 allowance prices to reduce the risk of facing substantial sanction payments or possible high prices for purchasing additional CO_2 allowances. For a thorough discussion of this issue see e.g. Bokenkamp et al. (2005).

Since the official start of spot and futures trading in 2005, a number of studies have investigated the price behavior of CO_2 spot or futures contracts, while only few studies have investigated the relationship between the two markets. Benz and Trück (2008), Seifert et al. (2008) as well as Paolella and Taschini (2008) provide an econometric analysis of the behavior of allowance prices and investigate different models for the dynamics of short-term spot prices. Conrad et al. (2011) model the adjustment process of EUA prices to the releases of announcements at high-frequency; they find that the decisions of the European Commission on National Allocation Plans have a strong and immediate impact on EUA prices and that EUA prices increase in response to better than expected news on the future economic development. Fehr and Hinz (2006) find that an additional fuel switching (coal $\rightarrow$ gas) mechanism significantly affects the spot price. Burtraw et al. (2002), Böhringer and Lange (2005) and Schleich et al. (2006) conduct simulation studies on CO_2 market prices with respect to changes in different market design parameters. Chevallier (2009a) examines the empirical relationship between the returns on carbon futures and changes in macroeconomic conditions and documents that carbon futures returns may be weakly forecast on the basis of two variables from the stock and bond markets, i.e. equity dividend yields and the 'junk bond' premium. Chevallier (2011) suggests that yearly compliance events, and growing uncertainties in post-Kyoto international agreements, may explain the instability in the volatility of carbon prices. Bredin and Muckley (2011) examine the extent to which fundamental factors, like economic growth, energy prices and weather conditions, determine the EUA futures prices during the period 2005-2009. Kara et al. (2008) examine the impacts of EU CO_2 emissions trading on electricity markets and consumers in Finland. Finally, examining emission allowance prices and derivatives, Daskalakis et al. (2009) find some evidence that market participants adopt standard no-arbitrage pricing.

However, the relationship between spot and futures prices in emission allowance markets has only rarely been investigated. exceptions include the work by Chevallier (2009b), Uhrig-Homburg and Wagner (2009), Milunovich and Joyeux (2010) and Madalena and Pinho (2011). Milunovich and Joyeux (2010) examine the issues of market efficiency and price discovery in the EU carbon futures market during the pilot trading period. The authors find that none of the carbon futures contracts examined are priced according to a cost-of-carry model. However, futures contracts referring to the pilot trading period form a stable long-run relationship with the spot price and can be considered as risk mitigation instruments. Interestingly, also examining the relationship between EU carbon spot and futures markets during the pilot period, Uhrig-Homburg and Wagner (2009) suggest that after an initial period of rather noisy pricing, the cost-of-carry model is largely found to hold. They report that while the convenience yield is not consistent over time and temporary deviations from the cost-of-carry linkage may exist they generally vanish after only a few days. The authors also conduct tests of causality and their results indicate that causality runs both ways, from futures to spot and from spot to futures. Unfortunately, the results of these two studies are limited to the first trading period where banking of allowances from the pilot to the later Kyoto commitment period was not allowed. Therefore, results on the cost-of-carry relationship between spot and futures contracts might be questionable, in particular when looking at inter-period relationships. Madalena and Pinho (2011) examine EUA spot and futures prices from an ex-post perspective also for the first Kyoto commitment period and find evidence for a significant negative risk premium (i.e. a positive forward premium) in the market. They also find a positive relationship between risk premiums and time-to-maturity of the futures contracts. Chevallier (2009b) investigates the modeling of the convenience yield in the EU-ETS using daily and intradaily measures of volatility. The author finds a non-linear relation between spot and futures prices and suggests that the dynamics of the observed convenience yield can be best described by a simple autoregressive process. None of these papers tries to model the whole term structure dynamics of spot and futures markets using a factor model approach. Therefore, our approach and focus significantly differs from previous studies on the issue.

For other commodities like oil or agricultural products, the connection between spot and futures prices and the convenience yield has been investigated more thoroughly. For pricing contingent claims in commodity markets Gibson and Schwartz (1990) present a two-factor model using the spot price and the instantaneous convenience yield as factors. With respect to the relationship between spot and futures prices the literature finds some evidence on expected spot prices often exceeding the futures price of such assets (Bodie and Rosansky, 1980; Chang, 1985; Pindyck, 2001). This situation is called normal backwardation and was initially suggested by Keynes (1930). Wei and Zhu (2006) find economically significant convenience yield and risk premiums in the U.S. natural gas market. However, for electricity prices there is also some evidence that futures prices may exceed expected spot prices, see e.g. Bierbrauer et al. (2007), Botterud et al. (2010), Longstaff and Wang (2004) and Weron (2008). Due to the peculiarity of the market for CO_2 emission allowances as well as the ambiguous results in different commodity markets, it seems worthwhile to compare the behavior of EUA spot and futures prices.

The aim of this paper is twofold. Our first goal is to provide a thorough analysis of the spot-futures price relationship in the EU-ETS, also in comparison to other commodity markets. We investigate correlations between spot and futures contracts, as well as the convenience yield and the volatility term structure for the pilot trading and Kyoto commitment period. We relate our results to general concepts of commodity market such as backwardation and contango market situation and the Samuelson effect. Our second objective is to capture the changing term structure dynamics in the EU-ETS spot and futures market. Hereby, we apply a novel dimension reduction technique – in the spirit of the Principal Components Analysis (Koekebakker and Ollmar, 2005; Ramsay and Silverman, 1997; Tolmasky and Hindanov, 2002) – and utilize dynamic semiparametric factor models (DSFM) for describing the term structure of futures contracts. Again, due to changing regulations on the banking of emission allowance contracts, we take into account the differences in the term structure dynamics between the initial pilot and the Kyoto commitment period. By investigating these issues, we also provide insights into participants' evaluation of risks in the market, their reaction to price shocks and their assumptions on future emission levels or allowances allocation for the second Kyoto commitment period.

The remainder of the paper is organized as follows. Section 2 reviews the relationship between spot and futures prices and explains the idea of normal backwardation or contango markets, as well as, the so-called Samuelson effect. It further illustrates the idea of the convenience yield as the benefit to the holder of commodity inventory. In section 3 we provide a brief description of the dynamic semiparametric factor model (DSFM) approach. Section 4 provides an empirical analysis on CO_2 spot and futures prices in the European Energy Exchange (EEX). We investigate the connection between EUA spot and futures prices and the convenience yield. We also examine the changes in this relationship through time and study the dynamics of the futures prices in the functional form by applying the DSFM approach. Section 5 concludes and gives suggestions for future work on the topic.

2. Commodity Spot and Futures Markets

An appropriate approach in specifying EUAs might be their consideration as a factor of production, see e.g. Fichtner (2004). Similar to other commodities, they can be 'exhausted' for the production of CO_2 and after their redemption they are removed from the market. Since a competitive commodity market is subject to stochastic fluctuations in both production and consumption, market participants will generally hold inventories. For emission allowances, producers may hold such inventories to reduce the costs of adjusting production over time or to avoid stockouts. Unlike for other factors of production, the amount of allowances has to match the actual production figure of the preceding calendar year only by April 30 of the next year. However, examining appropriate financial models for CO_2 emission allowances, the obvious parallels to a factor of production motivate the idea to adopt approaches from commodity markets rather then using typical financial

Table 1: Description of market situation based on the relationship between (expected) spot and futures price.

Market Situation	Relation between (expected) spot and futures price
Backwardation	$F_{t,T} \leq S_t$
Normal Backwardation	$F_{t,T} \leq E_t(S_T)$
Contango	$F_{t,T} > S_t$
Normal Contango	$F_{t,T} > E_t(S_T)$

models for asset pricing. Hence, in this section we will briefly review some features of commodity markets with focus on the relationship between the spot and futures markets.

2.1. Backwardation and Contango

The futures market is said to exhibit *backwardation* when the futures price $F_{t,T}$ is less than or equal to the current spot price S_t; it exhibits *normal backwardation* when the futures price is less than or equal to the expected spot price $E_t(S_T)$ at time T. On the other hand, the term *(normal) contango* is used to describe the opposite situation, when the futures price $F_{t,T}$ exceeds the (expected) spot price at time T. Table 1 summarizes the four different situations, see also Hull (2005) or Pindyck (2001).

The differences between spot and futures prices can be explained by a typical insurance contract: in the (normal) backwardation case the producers are buying insurance against falling prices, whereas in the contango case, consumers buy insurance against rising prices. The theory postulates that commodity futures markets usually exhibit backwardation and tend to rise over the life of a futures contract. Initially suggested by Keynes (1930) and Hicks (1946), the idea of backwardation assumes that hedgers tend to hold short positions as insurance against their cash position and must pay speculators a premium to hold long positions in order to offset their risk. Thus, observed futures prices $F_{t,T}$ with delivery at time T are often below the expected spot price $E_t(S_T)$. The notion of normal backwardation is equivalent to a positive risk premium since the risk is transferred to the long position in the futures contract; likewise normal contango is equivalent to a negative risk premium. Formally the *risk premium* is defined as the reward for holding a risky investment rather than a risk-free one. In other words, the risk premium is the difference between the expected spot price, which is the best estimate of the going rate of the asset at some specific time in the future, and the forward price, i.e. the actual price a trader is prepared to pay today for delivery of the asset in the future (Botterud et al., 2010; Diko et al., 2006; Pindyck, 2001; Weron, 2008). Note, that in the financial mathematics literature yet a different notion is used. The *market price of risk* (often denoted by λ) is defined as the difference between the drift in the original 'risky' probability measure P and the drift in the 'risk-neutral' measure P^λ in the stochastic differential equation governing the price dynamics (Weron, 2006). The spot price forecast $E_t(S_T)$ is the expected value of the spot price at some future date with respect to P, while the forward price $F_{t,T}$ is the expected value of the spot price with respect to P^λ. If λ is positive then the risk premium is also positive, and vice versa.

Another interesting issue is the term structure of a commodity's forward price volatility. Investigating the issue, Samuelson (1965) found a typically declining term structure in the volatility of futures prices as maturity increases. This behavior is referred to as the *Samuelson effect* or as the *time-to-maturity effect*. The behavior is generally explained by the fact that the opinion of investors of a distant future environment, including the evaluation of distant futures prices, is only subject to minor changes in the near future. Hereby, it is assumed that only few of the parameters affecting the final level of the prices will change today. Hence, only minor effects can be expected for futures with long maturities. However, as the maturity date is approached, investors are clearly more sensitive to information that influences the level of the futures price at maturity.

The empirical literature on backwardation or contango in commodity markets shows ambiguous results. While earlier studies find some evidence to support the normal backwardation idea for several products, recent studies also observe futures prices exceeding the expected future spot prices in empirical data. Bodie and Rosansky (1980) conduct an extensive study on risk and return of futures for major commodities traded in the United States. Combining futures contracts of selected commodities in a portfolio they find that the mean rate of return in the period from 1950 and 1976 clearly exceeded the average risk free rate. Chang (1985) also finds evidence of normal backwardation over the period from 1951 to 1980 examining futures prices of agricultural commodities like wheat, corn and soybeans. Fama and French (1987) combine a variety of commodities like metal or agricultural products into a portfolio and investigate the risk premium in futures prices. They find marginal evidence of normal backwardation, however, the risk premium in examined futures prices is not significantly different from zero. In a more recent study, Pindyck (2001) finds evidence for backwardation while investigating futures markets for crude and heating oil. In particular, the degree of backwardation is larger during times of high volatility. Considine and Larson (2001a,b) also find backwardation in crude oil and natural gas markets, while Milonas and Henker (2001) get similar results for international oil markets. However, there also some empirical studies suggesting contango markets. Longstaff and Wang (2004) examine whether the forward risk premium (i.e. the negative of the risk premium) paid in the PJM electricity market is significant. Their findings are both positive and negative risk premiums that vary systematically throughout the day. Weron (2008) studies Asian option and futures prices at the Scandinavian Nord Pool electricity market and finds that for most of the time market prices of risk are negative (which corresponds to negative risk premiums) and increasing (or equivalently decreasing with time to maturity). The negative (on average) risk premiums in the Nord Pool futures price data are also confirmed by Botterud et al. (2010) who analyze 11 years of historical data. Bierbrauer et al. (2007) obtain similar results for short and medium-term periods examining prices from the EEX electricity market. A reasonable explanation for negative risk premiums (i.e. contango markets) in electricity futures prices is a higher incentive for hedging on the demand side relative to the supply side, because of the non-storability of electricity as compared to the limited and costly but still existent storage capabilities of fuel (water, coal, oil, gas). Finally, investigating the Samuelson effect in an empirical study on the behavior of metal prices, Fama and French (1988) found that violations of this pattern may occur when inventory is high. In particular, forward price volatilities can initially increase with contract horizon.

2.2. Relating Spot and Futures Prices

Approaches for the valuation of forward and futures contracts can be conceptually divided into two groups (Fama and French, 1987). The first group suggests a risk premium to derive a model for the relationship between short-term and long-term prices. The second group is closely linked to the cost and convenience of holding inventories. In the following we follow the second approach and briefly illustrate the derivation of the convenience yield.

The convenience yield is usually derived within a no-arbitrage or cost-of-carry model which is based on considerations on a hedging strategy consisting of holding the underlying asset of the futures contract until maturity. Hereby, the long position in the underlying is funded by a short position in the money market account. Risk drivers determining the futures price in this case include the cost-of-storage for forwards on commodities, cost-of-delivery and interest rate risk. Differences between current spot prices and futures prices are explained by interest foregone in storing a commodity, warehousing costs and the so-called convenience yield on inventory. By assuming no possibilities for arbitrage between the spot and futures market, a formula for the convenience yield can be derived (Geman, 2005; Pindyck, 2001).

Assume that we hold one unit of emission rights at time t and the current spot price is S_t. Obviously there is no physical storage cost for holding an emission right. Hence, assuming the existence of a convenience yield, holding the emission right until T will pay us the stochastic return:

$$S_T - S_t + \gamma_{(T-t)}. \tag{1}$$

Hereby, $\gamma_{(T-t)}$ denotes the convenience yield for holding the emission right from t until T. Assume that at the same time we also short a futures contract written on the emission right with delivery in T. The return of this futures contract equals $F_{t,T} - S_T$. Note that there is no risk involved in the transactions and the total return is non-stochastic and should equal the risk-free rate for the period $T - t$ times the current spot price of the emission right:

$$S_T - S_t + \gamma_{(T-t)} + F_{t,T} - S_T = (e^{r(T-t)} - 1)S_t. \tag{2}$$

Solving for $\gamma_{(T-t)}$ we get the following equation for the (capitalized) flow of marginal convenience yield (Pindyck, 2001):

$$\gamma_{(T-t)} = S_t e^{r(T-t)} - F_{t,T}. \tag{3}$$

The convenience yield obtained from holding a commodity can be regarded as being similar to the dividend obtained from holding a company's stock. It represents the privilege of holding a unit of inventory, for instance, to be able to meet unexpected demand. According to Pindyck (2001) the spot price of a commodity can be explained similar to the price of a stock: like the price of a stock can be regarded as the present value of the expected future flow of dividends, the price of a commodity is the present value of the expected future flow of convenience yields.

3. Dynamic Semiparametric Factor Models

In this section we describe the dynamic semiparametic factor model (DSFM) that can be used to study the dynamics of daily emission allowance spot and futures prices in the functional form. Hereby, we consider the whole term structure of available spot and futures contracts to better understand the dynamics of the entire system. We apply the DSFM, which offers flexible modeling and allows for dimension reduction. The model was first proposed by Fengler et al. (2007) for studying the dynamics of implied volatility surfaces and further refined by Park et al. (2009) who implemented a series based estimator instead of a kernel smoother for the estimation. Recently, DSFM have also been applied to estimate the dynamic structure of risk neutral densities implied by option prices (Giacomini et al., 2009) as well as neuro economic analysis of experimentally controlled risk behaviour have evolved (Mysickova et al., 2011). Application to commodity markets include Borak and Weron (2008) who use the DSFM for approximation of electricity forward curve dynamics and Härdle and Trück (2011) who analyze the dynamics of hourly electricity spot prices.

Generally, the objective of factor analysis is dimension reduction in order to describe fluctuations over time in a set of usually high-dimensional variables through those experienced by a small set of factors. Hereby, observed variables are assumed to be linear combinations of the unobserved factors, with the factors being characterized up to scale and rotation transformations. For instance, a J-dimensional random vector $Y_t = (Y_{t,1}, ..., Y_{t,J})$ can be represented as an orthogonal L-factor model

$$Y_{t,j} = m_{0,j} + Z_{t,1}m_{1,j} + ... + Z_{t,L}m_{L,j} + \varepsilon_{t,j} \ , \tag{4}$$

where $Z_{t,l}$ are common factors, the coefficients $m_{l,j}$ are *factor loadings* and $\varepsilon_{t,j}$ are errors (or *specific factors*) that explain the residual part (Peña and Box, 1987). Normally, the index $t = 1, ...T$ represents the time evolution of the observed vector of variables and Y_t can be considered as a multi-dimensional time series. The advantage of applying factor analysis is that if a sufficiently high fraction of the variation of Y_t can be explained by the L factors, the study of high-dimensional Y_t can then be simplified to the modeling of $Z_t = (Z_{t,1}, ..., Z_{t,L})$, which is a more feasible task, in particular when $L << J$.

In comparison to a standard factor model, the DSFM allows for the incorporation of observable covariates $X_{t,j}$ while the factor loadings $m_{l,j}$ are now generalized to nonparametric functions of the covariates $m_l(X_{t,j})$, so that the standard factor model is extended to

$$Y_{t,j} = m_0(X_{t,j}) + \sum_{l=1}^{L} Z_{t,l}m_l(X_{t,j}) + \varepsilon_{t,j}. \tag{5}$$

As pointed out by Park et al. (2009), the DSFM can be regarded as a regression model with embedded time evolution. However, the model is different from varying-coefficient models, like in Fan et al. (2003) or Yang et al. (2006), since the series Z_t is actually unobservable. However, some linear models which allow time-varying coefficients, as considered in Hansen et al. (2004) and Brumback and Rice (1998), may be recognized as a special case of the DSFM setting.

For the task of modeling the term structure dynamics of emission allowance spot and futures prices, the DSFM structure can be exploited in order to reduce the dimension of observed price series to a smaller number of factors. Hereby, $Y_{t,j}$ are the EUA futures prices observed on day $t = 1, ..., T$ for delivery at time $j = 1, ..., J_t$ and $X_{t,j}$ denote the corresponding maturity dates. In our study we observe $J_t = 7$ futures contracts with delivery in 2006, 2007, ..., 2012 for Phase I of the EU-ETS and $J_t = 6$ futures contracts with delivery in 2009, 2010, ..., 2014 for Phase II. The whole term structure dynamics is then explained by the time propagation of the L factors and can be observed through the evolution of the time series $Z_{t,l}$. Note, that contrary to a parametric approach both m_l and $Z_{t,l}$ have to be estimated from the data. While Fengler et al. (2007) suggest the use of a nonparametric kernel estimator for the estimation of the loading functions $m_l(.)$, we follow Borak and Weron (2008) and Park et al. (2009) and implement a series estimator linearizing the loading functions with B-splines of the form

$$m_l(X_j) = \sum_{k=1}^{K} a_{l,k}\psi_k(X_j). \tag{6}$$

Hereby, K is the number of knots, $\psi(X) = (\psi_1, ..., \psi_K)^T(X_j)$ are the splines, and $A = (a_{l,k})$ denotes the appropriate coefficient matrix. The estimation procedure then determines the loading functions m_l and time series $Z_{t,l}$ that minimize the following least squares criterion

$$\sum_{t=1}^{T}\sum_{j=1}^{J_t}\left\{Y_{t,j} - \sum_{l=0}^{L} Z_{t,l}\sum_{k=1}^{K} a_{l,k}\psi_k(X_j)\right\}^2. \tag{7}$$

The estimation procedure is iterative. First the model size L is determined in advance. Next, starting from initial white noise sequences $\widehat{Z}_{t,l}^{(0)}$, $l = 1, ..., L$, the estimates $\widehat{m}_l^{(1)}$ are obtained. Then the updates $\widehat{Z}_{t,l}^{(1)}$ are calculated using $\widehat{m}_l^{(1)}$. The iterative steps are repeated consequently until a convergence criterion is met. Note, that the solution to this optimization problem is not unique. The signs of $Z_{t,l}$ and m_l cannot be identified such that certain linear transformations, like rotation, yield the same model for different functions m_l. A possible choice for the identification procedure is to choose the $\hat{m}_l$ to be orthogonal and then order them with respect to the variation of the series $\sum_{t=1}^{T} Z_{t,l}^2$ such that $\widehat{m}_0^{new}$, $\widehat{m}_1^{new}$ and $\widehat{Z}_{t,1}^{new}$ contain as much information on the variation as possible and explain the largest movements of Y_t. This ordering can be considered to be similar to ordering the factors in the Principal Components Analysis (PCA). What makes DSFM and PCA different is the calibration scheme. The DSFM is more flexible in this respect. It minimizes the squared residual (or maximizes the in-sample fit with respect to some score function), while a factor model estimated through PCA maximizes the expected variance (Ramsay and Silverman, 1997). For further issues on the estimation procedure and convergence of the algorithm we refer to Park et al. (2009), where also the question of statistical inference based on the estimated time series $\hat{Z}_{t,l}$ instead of the 'true' unobserved time series $Z_{t,l}$ is discussed.

For the choice of L we apply the following procedure. First, for different values of L, we calculate the proportion of the variation explained by the model compared to the simple invariate estimate given by the overall mean:

$$1 - RV(L) = 1 - \frac{\sum_t^T \sum_j^{J_t}\{Y_{t,j} - \sum_{l=0}^{L}\widehat{Z}_{t,l}\widehat{m}_l(X_{t,j})\}^2}{\sum_t^T \sum_j^{J_t}(Y_{t,j} - \bar{Y})^2}. \tag{8}$$

Since the model is not nested, the whole estimation procedure has to be repeated for different L's until the explanatory power of the model is considered to be sufficient.

4. Empirical Results

4.1. The Data

For our analysis we use available market quotes from the European Energy Exchange (EEX) and European Climate Exchange (ECX): EUA spot and Phase I futures prices from the EEX, while EUA Phase II and III futures quotes from the more liquid ECX. For the pilot trading period we consider spot and futures prices from October 4, 2005 to November 29, 2007, for the Kyoto commitment period for the period April 8, 2008 – July 31, 2009. Spot contracts for EU emission allowances have a contract volume of 1 ton CO_2 and are quoted in EUR with a precision of two decimal points. For the pilot trading period beginning on January 1, 2005 we consider 2006, 2007 and 2008 futures contracts, for the first Kyoto commitment period beginning on January 1, 2008 we consider 2008, 2009, ..., 2012 futures and for the second Kyoto commitment period beginning on January 1, 2013 we consider 2013 and 2014 futures contracts. The contract volume amounts to 1000 tons of CO_2 and the contracts expire on the last business day in November (for the EEX futures) or on the last business day in December (for the ECX futures). For every futures contract a settlement price, in accordance with the current spot market price is established on a daily basis. According to a daily profit and loss balancing (variation margin), the change in the value of a futures position is credited to the trading participant or debited from her in cash. For both markets, delivery of the EU emission allowances is carried out up to two business days after maturity of the contracts.

4.2. The Pilot Trading Period

We start with an analysis of the relationship between spot and futures prices for the pilot trading period. While spot trading started already in January 2005, when the EU-wide CO_2 emissions trading system entered into operation, futures contracts have been traded only since October 2005. Figure 1 displays CO_2 emission allowance spot prices for the pilot trading period from January 3, 2005 till December 28, 2007. At the commencement of trading, spot prices initially fell due to a quite mild climate and high supply of wind energy from Scandinavia and northern Germany. However, from February onwards an extreme cold snap and constant high UK gas and oil prices, compared to relatively low coal prices, led to a significant price increase within the next months. This effect was boosted by an extremely dry summer in the southwest of Europe. Especially in Spain, due to high temperatures and absence of rainfall, hydro-storage plants could not be fully utilized. Additionally, the lack of cooling water for nuclear power plants led to a higher power plant utilization and therefore increased the demand for CO_2 permits. Spot prices peaked on July 11 with 29.21 EUR but fell back to a level of approximately 22 EUR in August, remaining there until the end of 2005. Again, the beginning of an extremely cold winter in January 2006 led to a substantial increase in allowance prices up to 29.78 EUR on April 18, 2006.

Shortly after the April 2006 peak, news spread that a number of participating countries had given their industries too generous emission caps such that there was no need for them to reduce their emissions. On April 25, the Netherlands and Czech Republic announced that their emissions were 7% and 15% below the respective allocations. Prices fell dramatically within three weeks from 29.37 EUR on April 24 to 9.13 EUR on May 12. A renewed increase of spot prices to approximately 18 EUR could be observed until the end of May. Since then, a more or less continuing decrease in spot prices until the end of the trading period could be observed. By the beginning of January 2007 the prices had already decreased to approximately 5 EUR while by the end of March 2007 prices for the first time dropped below 1 EUR. Since then, they steadily declined and on the last trading day (December 28, 2007) a price of 0.02 EUR was observed.

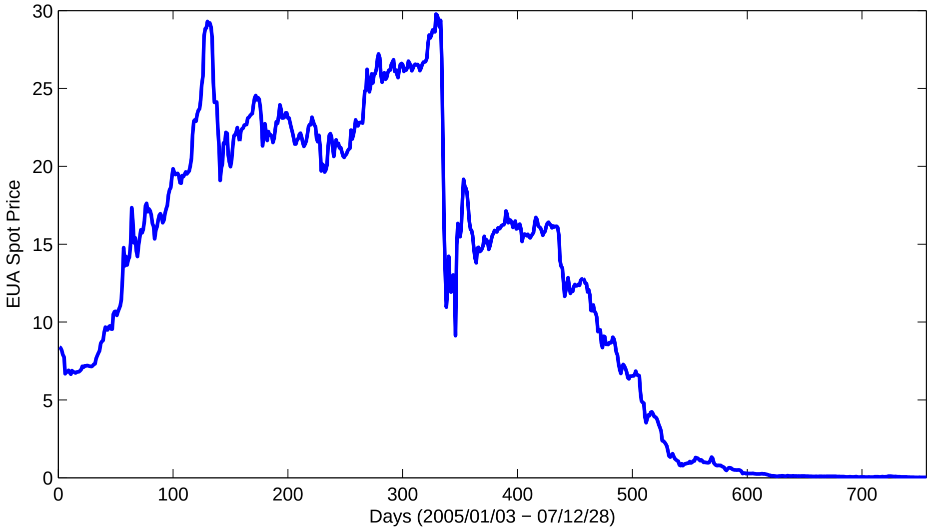

Figure 1: EUA spot price for the pilot trading period from January 3, 2005 to December 28, 2007. Note, that the time scale uses business days, i.e. there are approximately 250 observations per year.

To investigate the relationship between spot and futures allowance prices, we consider the time period starting from October 4, 2005, when the trading of futures contracts commenced at the EEX. The left panel of Figure 2 displays spot and emission allowance pilot period futures prices for delivery in November 2007 and the first Kyoto period futures with delivery in November 2008. We find that while there is a strong similarity between spot and futures prices with delivery in 2006, futures prices for the Kyoto period show clearly less co-movement with the spot market. Note, that during this time period no futures contracts for the second Kyoto commitment period were traded yet.

Tables 2 and 3 report the correlation coefficients between daily returns of emission allowances' spot and futures prices for the period from October 4, 2005 to April 24, 2006, i.e. before the news

Table 2: Correlations between returns from spot and futures contracts for the pilot period (2006, 2007) and Kyoto commitment period (2008-2012) for market quotes from October 4, 2005 to April 24, 2006.

Delivery	Spot	2006	2007	2008	2009	2010	2011	2012
Spot	1	0.967	0.966	0.817	0.831	0.818	0.810	0.802
2006		1	0.998	0.835	0.846	0.835	0.830	0.821
2007			1	0.833	0.844	0.833	0.828	0.819
2008				1	0.991	0.980	0.974	0.967
2009					1	0.988	0.983	0.976
2010						1	0.997	0.993
2011							1	0.998

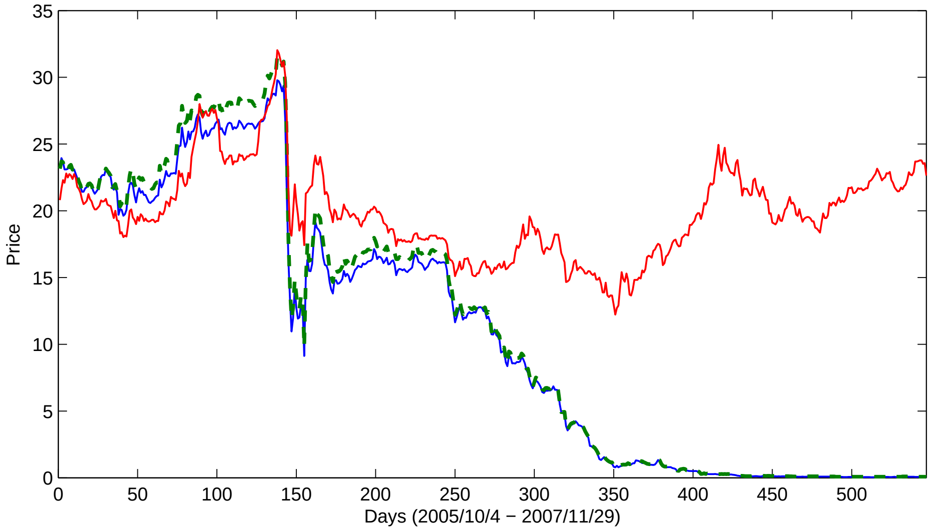

Figure 2: EUA spot price (solid blue) and futures prices for delivery in 2007 (dashed green) and 2008 (solid red) for October 4, 2005 to November 29, 2007. Note, that the time scale uses business days, i.e. there are approximately 250 observations per year.

of overallocation was spread, and for the whole pilot trading period. Let us first consider the time period before the significant drop of spot prices in April/May 2006. The results confirm the observation of Figure 2: there is a very strong correlation between the returns of spot and pilot period futures prices, yielding $\rho > 0.9$ for futures with delivery in 2006 and 2007. The correlation between spot returns and returns of futures contracts for the Kyoto period is clearly lower but still significant, yielding correlations between 0.83 and 0.80. In general, the correlation is slightly decreasing with maturity, indicating that opinions of investors of a distant future environment are less affected by short-term price movements. Hence, we find some evidence on the Samuelson or time-to-maturity effect. Further we observe that the returns of futures contracts for the same trading period – either the pilot or the Kyoto period – also show very high correlations. For the pilot period we get $\rho = 0.998$ while for the Kyoto commitment period correlations are between 0.967 and 0.998.

We get a quite different picture if we consider correlations for the whole pilot trading period, also including data after the market crash in May 2006. Correlations between returns of spot and futures returns within the same trading period remain still high, while the correlation between spot and Kyoto period futures returns drop significantly. We interprete this in a way that after the news of overallocation, the price signal given by prices from contracts of the Kyoto committment period was not relevant anymore for the pilot trading period and vice versa.

Figure 3 displays the term structure of emission allowance spot and futures prices with yearly maturities from November 2006 to November 2012. For each trading day in October 2005, January 2006, March 2006 and November 2006 the daily observed spot and futures prices are connected by a smoothed line using cubic interpolation. We find that the term structure of futures prices is dynamic and shows quite different behavior through time. During the initial trading period in

Table 3: Correlations between returns from spot and futures contracts for the pilot period (2006, 2007) and Kyoto commitment period (2008-2012) for market quotes from October 4, 2005 to November 29, 2007.

Delivery	Spot	2006	2007	2008	2009	2010	2011	2012
Spot	1	0.969	0.835	0.297	0.302	0.313	0.300	0.298
2006		1	0.998	0.807	0.815	0.806	0.802	0.792
2007			1	0.506	0.506	0.505	0.503	0.502
2008				1	0.992	0.981	0.975	0.965
2009					1	0.988	0.982	0.972
2010						1	0.993	0.985
2011							1	0.992

October 2005 futures prices both for the pilot and Kyoto periods were slightly below current spot prices. While there was a quite flat term structure for the pilot period, a slightly increasing term structure of futures prices could be observed for the Kyoto commitment period. In January 2006, for the pilot period an increasing term structure can be observed while the term structure for the Kyoto period is only slightly increasing. Futures prices for the Kyoto commitment period are still below the spot price and futures prices of the pilot period. In May 2006, after the news of overallocation of emission rights in a number of European countries was published, futures prices for the Kyoto period are slightly higher than the spot and pilot period futures prices. In September 2006, a clearly increasing term structure can be observed and futures prices for the Kyoto period are significantly above the spot and pilot period futures prices. We conclude that starting from May 2006 the relationship between pilot period spot and futures and Kyoto commitment period futures prices showed significant changes. While the spot and also Phase I futures prices dropped significantly due to the news of overallocation of allowances, Kyoto period futures contracts were clearly less affected by these news. The latter can be attributed to the fact that no banking of allowances from the pilot to the later Kyoto commitment period was allowed. Further, market participants were aware that new allocation plans would be negotiated for the Kyoto commitment period that would most likely be below allocations for the pilot trading period.

We will now investigate the behavior of the convenience yield of CO_2 emission allowance futures prices for the pilot trading period. The necessary risk free rates were obtained using 3-month and 6-month Euribor rates for short-term periods and swap based zero coupon yields for the long-term interest rates up to 2012. To match the yields for different time horizons we used linear interpolation. Recall that under the standard cost-of-carry approach, we would expect the convenience yield to be zero such that the equation $F_{(t,T)} = e^{r(T-t)} S_t$ holds. Given equation (3), in the following we consider absolute values of the convenience yield as $\gamma_{(T-t)} = S_t e^{r(T-t)} - F_{t,T}$.

Figure 4 displays the convenience yield for the pilot period futures contract with delivery in November 2006 and November 2007. We find that the convenience yield was initially significantly different from zero for both contracts. This confirms results by other studies, e.g. Milunovich and Joyeux (2010) who report that none of the pilot period carbon futures contracts are priced according to a cost-of-carry model relationship. These authors argue that the mis-pricing could be

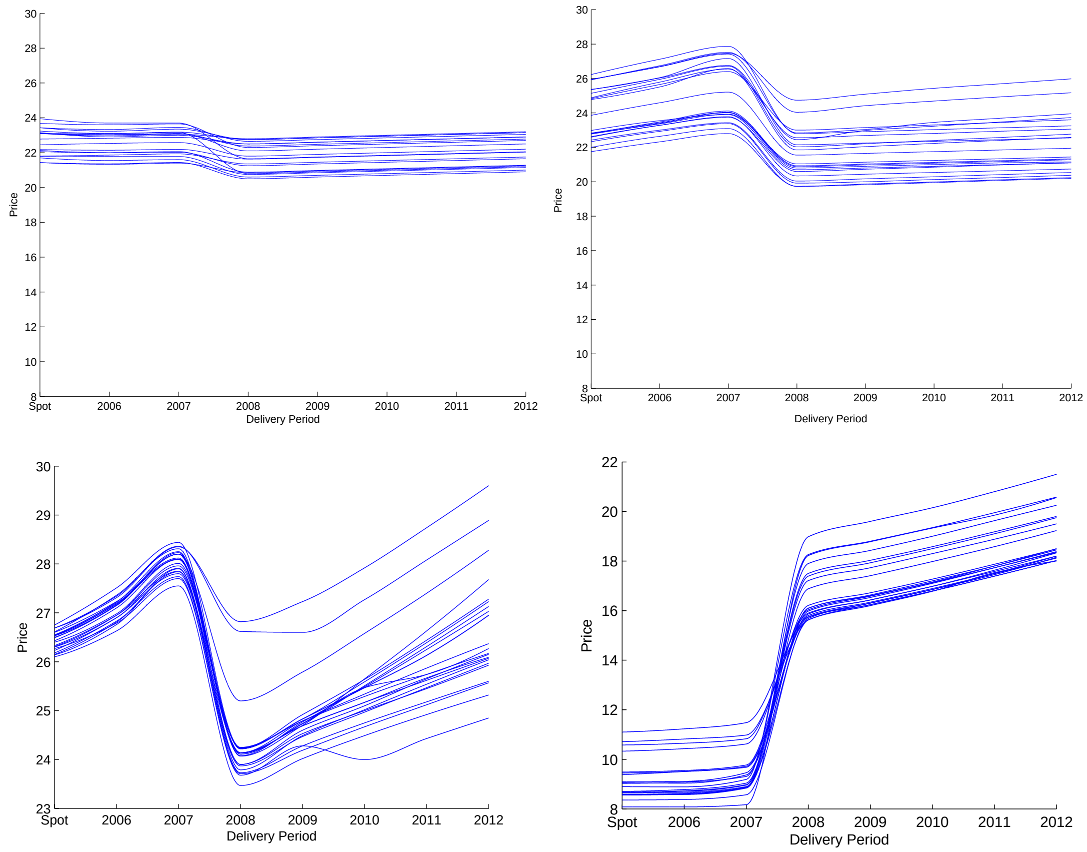

Figure 3: Term structure for spot and futures prices for each trading day of October 4 – 31, 2005 (*upper left panel*), January 1 – 31, 2006 (*upper right panel*), March 1 – 31, 2006 (*lower left panel*) and November 1 – 30, 2006 (*lower right panel*).

due to a large standard error associated with the estimated parameter on the interest rate variable. We can also observe three substantial shocks or rather short-lasting spikes in the convenience yield time series, indicating a reaction of the spot/futures price relationship to market news. The most significant one is observed in April 2006 when due to the news of overallocation the convenience yield suddenly became negative as a consequence of the spot price dropping substantially while 2006 and 2007 futures prices still remained on a higher level for a short period of time. The closer we get to the end of the pilot trading period, the smaller becomes the convenience yield. Due to the overallocation of allowances for this period, also the price for the 2007 futures contract approaches zero.

Overall, our findings suggest that considering the fact that banking and borrowing of allowances was allowed during the pilot period, initially there were potential arbitrage opportunities in the market for carbon permits. Since, at least for the first 6 months of trading, convenience yields were significantly different from zero and none of the futures contracts followed a cost-of-carry relationship with the spot price, market participants should have been able to apply trading strategies in order to achieve riskless profits.

Quite different results for the relationship between spot and futures prices can be obtained for

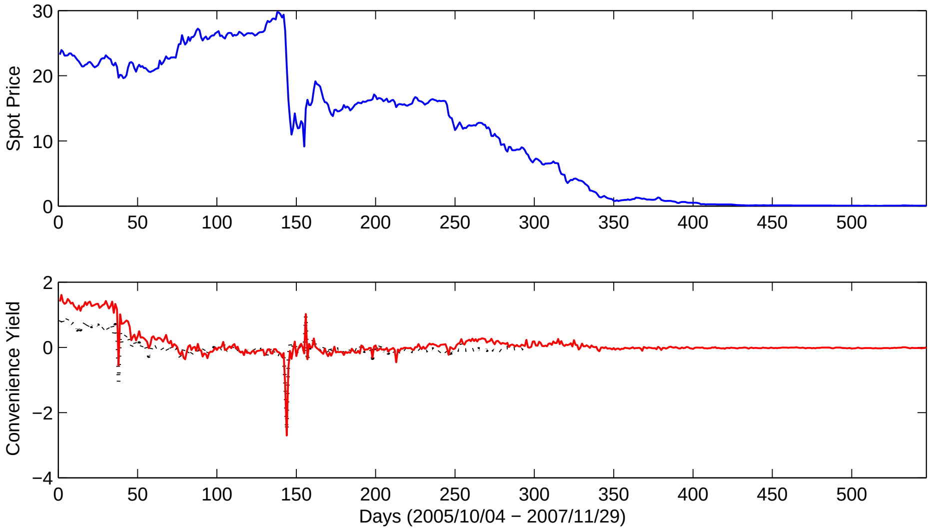

Figure 4: *Upper panel:* Spot prices (EUR/ton) from October 4, 2005 to November 29, 2007. *Lower panel:* Convenience yields (EUR/ton) for 2006 (dotted black) and 2007 (solid red) EUA futures.

the Kyoto commitment period futures. Note, however, that due to new allocation plans for the Kyoto commitment period, the term 'convenience yield' is not really appropriate, since pilot and Kyoto period contracts refer to different trading periods and thus, also to products that are subject to different levels of scarcity. Since banking of pilot trading period allowances for usage during the Kyoto commitment period was prohibited there was no immediate benefit of holding pilot period spot contracts with regards to the Kyoto commitment period. In the following, we will still refer to the difference between the spot and discounted futures price as 'convenience yield', however, we are aware that the use of this term might be somehow misleading. As indicated by Figure 5 which shows the 'convenience yield' for 2008 and 2012 futures contracts, during the first six months of trading the yield was clearly positive with values $0 < \gamma < 10$. After the news of overallocation of allowances for the pilot period was published, initially the price shock on allowances obviously affected the convenience yield for Kyoto period futures contracts similar to the ones for the pilot trading period. However, the persistence of the shock on convenience yields was of an entirely different nature: for the 2006 and 2007 futures, after a very short period with negative yields of approximately -2.5, also the futures prices for the pilot period adapted to the price change quickly and convenience yields approached zero. On the other hand, for Kyoto period futures contracts, the effect of the price shock on futures prices was not as dramatic as for the pilot period. The prohibition of banking between Phase I and Phase II and expected new NAPs for the Kyoto commitment period kept futures prices on a higher level between 12 and 25 EUR until the end of the pilot trading period in 2007. Thus, as illustrated in Figure 5, the 'convenience yield' for the 2008-2012 futures contracts became significantly negative. As the price of the spot contract approaches zero, it basically equals minus one times the futures price; compare Figures 2 and 5. Overall the analysis of pilot period spot and Kyoto commitment period futures prices reveals the following relationship: while in the beginning pilot period spot prices were also considered

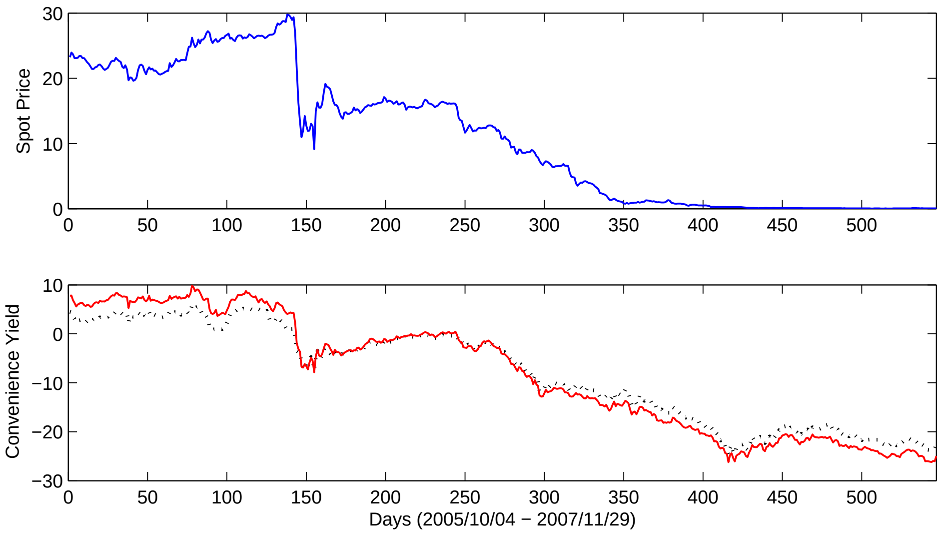

Figure 5: *Upper panel:* Spot prices (EUR/ton) from October 4, 2005 to November 29, 2007. *Lower panel:* 'Convenience yields' (EUR/ton) for 2008 (dotted black) and 2012 (solid red) EUA futures contracts.

as an indication for Kyoto commitment period allowance prices, after the news of overallocation, the importance of Phase I prices for Phase II futures prices dropped dramatically. Significantly higher prices for the Kyoto commitment period futures contracts indicate that market participants saw no privilege in holding the spot contract with respect to future periods. The major reason for this were the prohibition of banking between the pilot trading and Kyoto commitment period and market participants' expectations on lower allocations of allowances for the Kyoto commitment period.

4.3. The Kyoto Commitment Period

In the following we will now consider the relationship between spot and futures contracts for the Kyoto commitment period using data from April 8, 2008 to July 31,2009. Figure 6 provides a plot of the observed convenience yield for Kyoto commitment spot and futures contracts based on the simple cost-of-carry model described in Section 2. Similar to the pilot trading period, the market started in backwardation, with positive convenience yields indicating that the spot price was above the discounted price of Kyoto commitment period futures contracts. We also conducted t-tests that indicate convenience yields being significantly greater than zero for 2011 and 2012 futures contracts during the period from April to July 2008. In the course of time, the market situation changed from backwardation to contango in July 2009. During the period from April to July 2009, the convenience yield for 2011 and 2012 futures contracts was significantly smaller than zero. Overall, we find that similar to the pilot period none of the spot or futures contracts were priced according to the cost-of-carry relationship. The effect is more pronounced for futures contracts with longer maturity, like contracts maturing in December 2011 or 2012. The significantly negative convenience yield for the Kyoto period futures in 2009 indicates that market participants saw no privilege in holding the allowance now with respect to future periods.

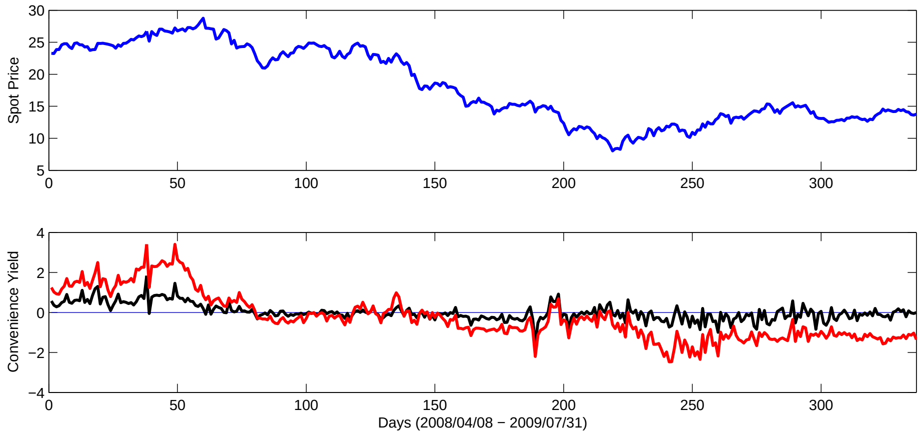

Figure 6: *Upper panel:* Spot prices (EUR/ton) from April 8, 2008 to July 31, 2009. *Lower panel:* Convenience yields (EUR/ton) for 2009 (black) and 2012 (red) EUA futures contracts.

As banking and borrowing within the years of the Kyoto commitment period (i.e. 2008-2012) is allowed, one could argue that the deviation from the cost-of-carry relationship is due to a large standard error associated with the estimated parameter on the interest rate variable or to different market expectations about interest rates in forthcoming years. Recall that due to the financial crisis interest rates in the Eurozone were at an extremely low level at the end of 2008 and during the considered period in 2009.

Very similar results are obtained for the relationship between Phase II spot and Phase III futures prices. Note, that the EU-ETS enables market participants to use Phase II permits also during Phase III such that banking will be allowed. On the other hand, borrowing of permits from Phase III and using the allowances in Phase II is not allowed. Again we find that the market has changed from initial backwardation to contango. The significantly negative convenience yields for the Phase III futures contracts indicate that market participants rather tend to hold long futures positions than the spot. One major reason for this could be the expectations on lower allocations of allowances for the third trading period. Similar to Phase II it is expected that new NAPs will be negotiated before Phase III.

Figure 8 displays the volatility term structure for spot and futures prices with delivery in December 2009 until December 2014. According to the Samuelson effect we would expect a declining term structure of the forward price volatility. Obviously, also the volatility term structure of spot and futures prices shows strong dynamics through time. Considering the period from July 1, 2008 to September 30, 2008, the volatility of futures contracts for Phase II and Phase III was higher than the spot price volatility. Quite different results are obtained when the period from April 1 to June 30, 2009 is examined. Here, the volatility term structure is quite flat, while in other subperiods even a decreasing volatility term structure could be observed. Overall, we find a rapidly changing behavior of the volatility term structure through time that often contradicts the Samuelson effect. In fact, for many periods the volatility of futures contracts with later maturity is significantly higher than the volatility of spot prices. This complex behavior requires efficient modeling tools that can reduce the dimensionality of the problem without a significant loss of

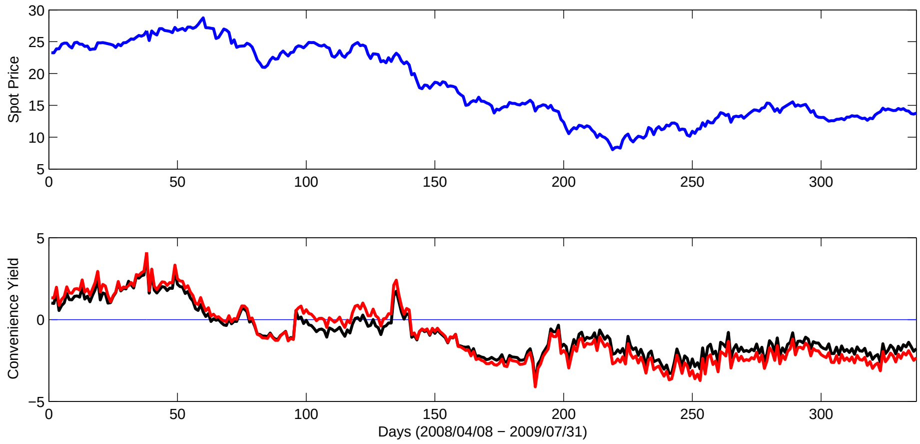

Figure 7: *Upper panel:* Spot prices (EUR/ton) from April 8, 2008 to July 31, 2009. *Lower panel:* Convenience yields (EUR/ton) for 2013 (black) and 2014 (red) EUA futures contracts.

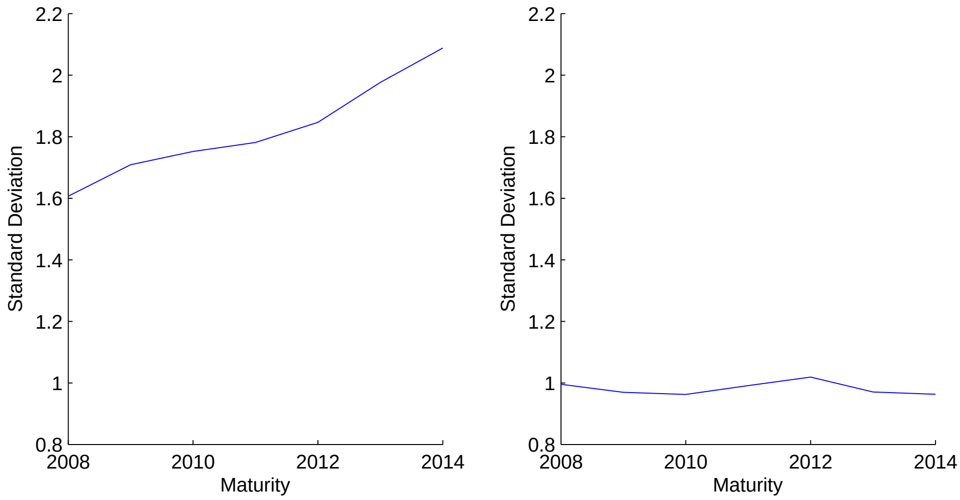

Figure 8: Volatility term structure of daily prices for the considered spot and 2009-2014 December futures contracts for the trading period July 1, 2008 – September 30, 2008 (*left panel*) and April 1 – June 30, 2009 (*right panel*).

Table 4: Explained variance for the models with $L = 1, 2$ and 3 dynamic factors for spot contracts as well as Phase I and Phase II futures contracts during the pilot trading period (October 4, 2005 to November 29, 2007).

No. Factors	$1 - RV(L)$
L=1	0.9562
L=2	0.9856
L=3	0.9858

information. Therefore, in the following Section we will use the DFSM approach to analyze the term structure of EUA futures prices. Such an analysis may provide market participants with a parsimonious model of forward price dynamics.

4.4. Dynamic Semiparametric Factor Modeling of Futures Prices

Up till now we have treated each futures contract separately and performed a comparative analysis. Now we consider the whole term structure of the futures contracts to better understand the dynamics of the entire system. We apply the dynamic semiparametric factor model (DSFM) introduced in Section 3 to study the dynamics of the futures prices in the functional form.

For the optimal choice of the number of factors L we apply the following procedure. First, for different values of L, we calculate the proportion of the variation explained by the model compared to the simple invariate estimate given by the overall mean, see (8). Since the model is not nested, the whole estimation procedure has to be repeated for different L's. In Table 4 we present the estimation results for $L = 1, 2$ and 3. Then we proceed like in the principal components analysis and limit our model to the number of factors which explain a sufficiently high percentage of the variance.

Let us first consider the results for prices of spot, Phase I and Phase II futures contracts during the pilot trading period. As indicated in Table 4, the inclusion of a third function only slightly improves the explanatory power of the fit and, therefore, from now on we only use the model with $L = 2$ basis functions. The estimated factor functions $\widehat{m}_1$ and $\widehat{m}_2$ and time series $\widehat{Z}_{t,1}$ and $\widehat{Z}_{t,2}$ are plotted in Figure 9 and refer to the considered time period from October 4, 2005 to November 29, 2007 during the pilot trading period. The first function is relatively flat, but slightly upward sloping with increasing maturity of the considered futures contracts. It can possibly be interpreted as level changes of the whole term structure with higher prices for futures contracts with longer maturity. The second function exhibits a more pronounced drop for maturities between two and three years. In our analysis, this coincides with the end of the pilot trading period (2007 futures contract) and the beginning of the Kyoto period (2008 futures contract). Overall, the function yields significant positive values for futures contracts with maturities during the pilot trading period and yields values around zero or small negative values for futures contracts with maturity during the first Kyoto commitment period.

Therefore, the positive values of $\widehat{Z}_{t,2}$ during the first 150 trading days reflect the initially higher prices of futures contracts with delivery during the pilot trading period in comparison to futures contracts with maturity in later years. After the significant drop of the spot price in May 2006,

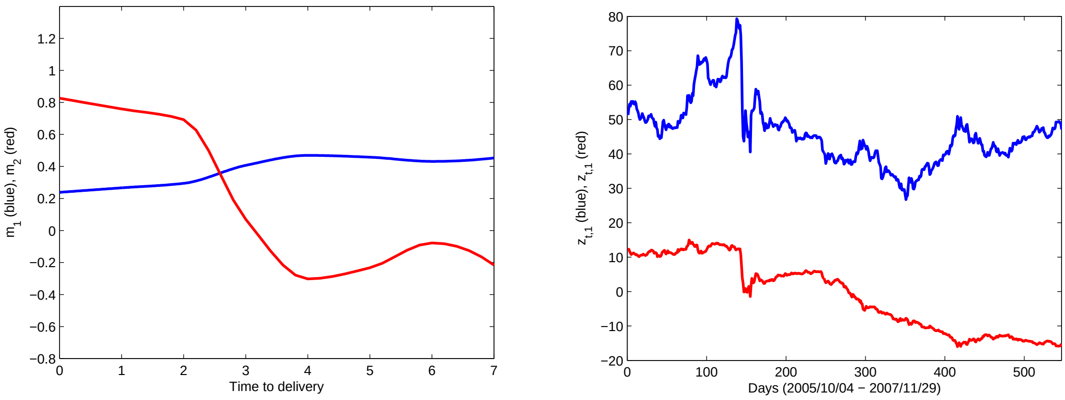

Figure 9: *Left panel:* Estimated basis functions $\widehat{m}_1$ (blue curve) and $\widehat{m}_2$ (red curve) for the pilot trading period (for data from October 4, 2005 to November 29, 2007). The time to delivery is measured in years. *Right panel:* Time series $\widehat{Z}_{t,1}$ (blue line) and $\widehat{Z}_{t,2}$ (red line) for this dataset.

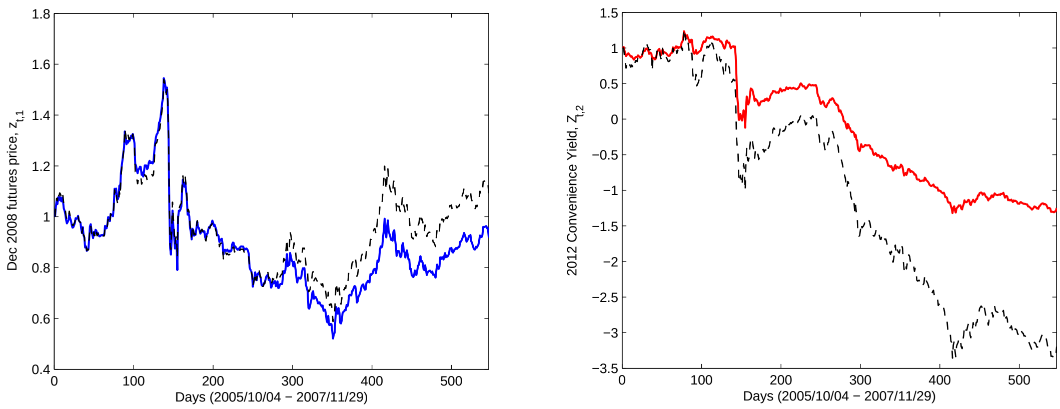

Figure 10: *Left panel:* The series $\widehat{Z}_{t,1}$ (solid, blue curve) together with ECX Dec 2008 futures prices (dashed, black curve) during the pilot trading period. *Right panel:* The series $\widehat{Z}_{t,2}$ (solid, red curve) together with the convenience yields for the 2012 futures contracts (dashed, black curve) during the pilot trading period (October 4, 2005 to November 29, 2007). For visual purposes all series were rescaled by the first value of the respective series.

Table 5: Explained variance for the models with $L = 1, 2$ and 3 dynamic factors for Phase II and Phase III futures contracts during the Kyoto commitment period (April 8, 2008 to July 31, 2009).

No. Factors	$1 - RV(L)$
L=1	0.9618
L=2	0.9914
L=3	0.9922

$\widehat{Z}_{t,2}$ decreases and yields significant negative values from December 2006 – approximately trading day 280 – onwards. This corresponds to the much higher prices of Phase II futures contracts in the end of 2006 and during 2007, where prices of spot and futures contracts referring to Phase I continue to drop significantly and slowly approach zero. Overall, a DSFM approach with two factor functions provides an almost complete description of the term structure dynamics of EUA spot and futures contracts during the pilot trading period.

To complete our analysis for the first trading period, in Figure 10, we plot $\widehat{Z}_{t,1}$ together with the ECX 2008 futures price and $\widehat{Z}_{t,2}$ together with the convenience yields for the 2012 futures contract. For visual purposes all series were rescaled by the first value of the respective series. The main factor which drives the level of the term structure is closely related to the dynamics of the 2008 futures price. The second factor, however, mirrors the convenience yields of futures contracts with delivery in Phase II. This result also confirms our previous findings that convenience yields can be interpreted as the market participants' expectations on allocations for the commitment trading period. When the corresponding convenience yields are negative, the prices of futures contracts with delivery during the Kyoto commitment period are relatively high in comparison to prices of pilot period futures contracts. This is caused by expected scarcity of allowances for the Kyoto commitment period while market participants expect to have a sufficient amount of allowances to fulfill their obligations during the pilot trading period.

We obtain similar results for the Kyoto commitment period (for data from April 8, 2008 to July 31, 2009). As Table 5 indicates, the inclusion of the third function only slightly improves the explanatory power of the fit such that, also for this period, a model with 2 basis functions is considered to be sufficient to describe the term structure dynamics. Similar to the analysis for Phase I, we plot the estimated factor functions $\widehat{m}_1$ and $\widehat{m}_2$ and time series $\widehat{Z}_{t,1}$ and $\widehat{Z}_{t,2}$ in Figure 11. Again, we observe, that the first factor function is relatively flat but slightly increasing and can be interpreted as modeling level changes of the whole term structure. Therefore, futures contracts with longer maturities yield higher prices than the spot or futures contracts with delivery periods in Phase II, e.g. in 2009 or 2010. The second function is more steep and increases significantly with maturity of the futures contract. Unlike for the analysis of the term structure of futures prices during the pilot trading period, there is no significant break between futures contracts referring to different trading periods. The reason for this may be that banking of allowances between Phase I and Phase II was not feasible while it is allowed between Phase II and Phase III. Again, the form of the function is indicative of a different behavior of the futures prices depending on the maturity of the contracts. The function is significantly negative for really short maturities and significantly

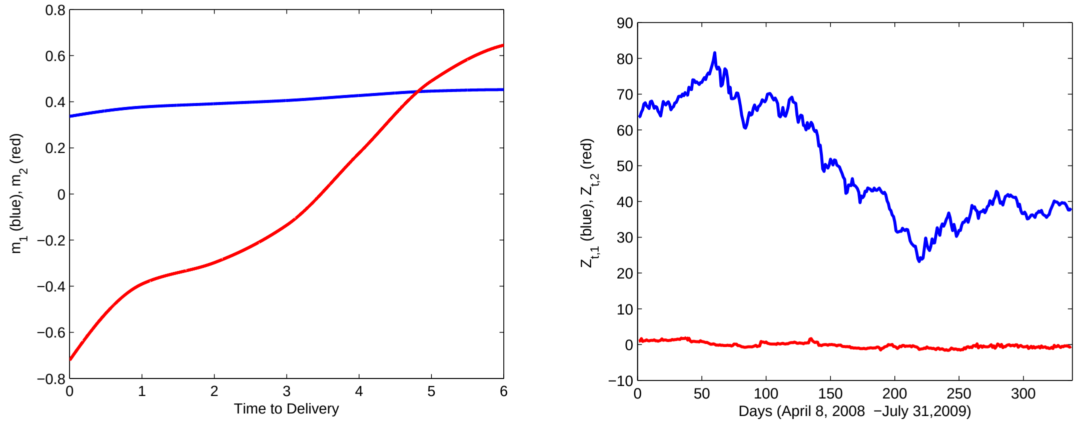

Figure 11: *Left panel:* Estimated basis functions $\widehat{m}_1$ (blue curve) and $\widehat{m}_2$ (red curve) during the Kyoto commitment period (for data from April 8, 2008 to July 31, 2009). *Right panel:* Time series $\widehat{Z}_{t,1}$ (blue line) and $\widehat{Z}_{t,2}$ (red line) for this dataset.

positive for long maturities.

In Figure 12, we plot $\widehat{Z}_{t,1}$ together with the spot price during the considered time period from April 8, 2008 to July 31, 2009 and $\widehat{Z}_{t,2}$ together with the convenience yields of the 2014 futures during the same time period. Again, for visual purposes all series were rescaled by the first value of the respective series. The main factor which drives the level of the term structure is closely related to the dynamics of the spot price. The estimated coefficient of correlation for the returns of the two series is approximately 0.80. The second factor, however, mirrors the convenience yields of futures contracts with longer maturities. The co-movement of the factor and the convenience yield of the 2014 futures contract as indicated in the right hand panel of Figure 12. This result confirms our previous findings that convenience yields can be interpreted as the market participants' expectations on allocations for the second Kyoto commitment trading period. When the corresponding convenience yields are negative, the prices of futures contracts with delivery in Phase III are relatively high compared to the prices of futures contracts with maturity in the Kyoto commitment period. This could be caused by the fear of a shortage of allowances in Phase III in comparison to Phase II. Similarly the flattening of the term structure, which is related to convenience yields being close to 0, corresponds to the lack of strong expectations on the scarceness of allowances when comparing Phase II and Phase III. Recall that when convenience yields are close to zero, pricing of allowance futures contracts is in line with the standard cost-of-carry approach.

4.5. *DSFM and the Gibson-Schwartz model*

Interestingly, the results of our empirical analysis using DSFM models can also be related to the classic model for pricing contingent claims in commodity markets initially suggested by Gibson and Schwartz (1990). In their seminal paper the authors present a two-factor model using the spot price and the instantaneous convenience yield as factors. As illustrated above, using the DSFM approach, we also identify two factors that explain a significant fraction of the whole term structure dynamics. Overall, a DSFM model with two factors explains approximately 98.56% of

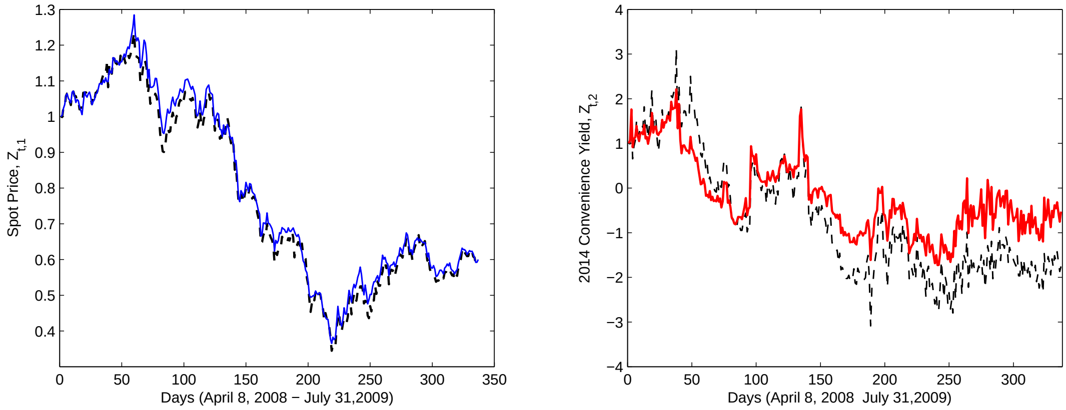

Figure 12: *Left panel:* The series $\widehat{Z}_{t,1}$ (solid, blue curve) together with the spot prices (dashed, black curve) during the Kyoto commitment period (for data from April 8, 2008 to July 31, 2009). *Right panel:* The series $\widehat{Z}_{t,2}$ (solid, red curve) together with the convenience yields for the 2014 futures contracts (dashed, black curve) for the same dataset. For visual purposes all series were rescaled by the first value of the respective series.

the total variance for Phase I/II spot and futures contracts while for Phase II/III our model explains 99.14% of the total variance. Furthermore, we find that in particular for the Kyoto commitment period, the time series of coefficients $\widehat{Z}_{t,1}$ and $\widehat{Z}_{t,2}$ for the identified factors follow a very similar pattern to the factors suggested in the Gibson-Schwartz model: our main factor which drives the level of the term structure is closely related to the dynamics of the spot price and the pattern of the series for the second identified factor mirrors the behavior of the convenience yield for the futures contract with the longest maturity. For the pilot trading period $\widehat{Z}_{t,1}$ is closely related to the price of the 2008 futures contract, while $\widehat{Z}_{t,2}$ again mirrors the behavior of the convenience yield for the futures contract with the longest maturity. These are quite interesting results given that in the DSFM approach both the basis functions and the evolution of the coefficients are estimated in a nonparametric way from the data only. Therefore, our results can be interpreted as an indication that the Gibson-Schwartz two-factor model could be applied to the pricing of intra- and inter-period emission allowances derivatives contracts.

5. Conclusions

In this paper we have conducted an empirical study on the relation between the EU CO_2 allowances' spot and futures prices. In particular we have examined the correlations of spot and futures contracts and the convenience yield.

Our findings are a quite dynamic behavior of the term structure for allowance prices and volatilities. While in general correlations between spot and futures prices decrease with time to maturity, the term structure of EUA prices shows significant changes through time. We observe that both for the pilot trading and Kyoto commitment period the market has changed from initial backwardation to contango. Thus, we observe futures prices that are clearly higher than the current spot price and deviate from the standard cost-of-carry approach. Also the term structure of volatilities for spot and futures prices is subject to several changes. We find an overall increasing price volatility with maturity for both periods. This somehow contradicts the time-to-maturity or Samuelson effect that suggests a typically declining term structure in the volatility of futures prices as maturity increases. Furthermore, the observed convenience yields in futures contracts are significantly different from zero, in particular for contracts with longer maturities. While this can be explained by the prohibition of banking when Phase I and Phase II prices are compared, it is more difficult to understand for the relationship between Phase II spot and Phase III futures contracts. One reason for the prevailing contango market situation may be expectations of market participants about potentially lower new National Allocation Plans in forthcoming years.

To better understand the dynamics of the whole term structure of futures contracts, we have applied the dynamic semiparametric factor model (DSFM). We find that a model with two factors, respectively two basis functions, explains a sufficiently high percentage of the variance for both trading periods. Hereby, for the Kyoto commitment period, the main factor which drives the level of the term structure is closely related to the dynamics of the spot price, while the second factor mirrors the convenience yields of futures with long maturities. Interestingly, our DSFM results can also be related to the classic Gibson-Schwartz two-factor model for pricing contingent claims in commodity markets that uses the spot price and the instantaneous convenience yield as factors. This is even more remarkable as in the DSFM approach both the basis functions for the factors and the evolution of the coefficients are estimated in a nonparametric way from the data without any prespecified assumptions about the factors. Our results might point towards future applications of the Gibson-Schwartz model for pricing of intra- and inter-period emission allowance derivative contracts.

We conclude that the price behavior of emission allowances in the spot and futures market is substantially different to those of other commodities. In terms of market participants' behavior, the current contango market situation with negative convenience yields can be interpreted as expectations on the price risk of CO_2 emissions allowances and the notion of forthcoming new allocation plans in the EU for future trading periods.

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