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Convenience Yields and Risk Premiums in the EU-ETS - Evidence from the Kyoto Commitment Period

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Convenience Yields and Risk Premiums in the EU-ETS - Evidence from the Kyoto Commitment Period[☆]

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Abstract

We examine convenience yields and risk premiums in the EU-wide CO_2 emissions trading scheme (EU-ETS) during the first Kyoto commitment period (2008-2012). We find that the market has changed from initial backwardation to contango with significantly negative convenience yields in futures contracts. We further examine the impact of interest rate levels in the Eurozone, the increasing level of surplus allowances and banking as well as returns, variance or skewness in the EU-ETS spot market. Our findings suggest that the drop in risk-free rates during and after the financial crisis has impacted on the deviation from the cost-of-carry relationship for emission allowances (EUA) futures contracts. Our results also illustrate a negative relationship between convenience yields and the increasing level of inventory during the first Kyoto commitment period, providing an explanation for the high negative convenience yields. Finally, we find that market participants are willing to pay an additional risk premium in the futures market for a hedge against increased volatility in EUA prices. Overall, our results contribute to the literature on the determinants and empirical properties of convenience yields and risk premiums for this relatively new class of assets.

Keywords: CO_2 Emissions Trading, Commodity Markets, Spot and Futures Prices, Convenience Yields, Risk Premiums.
JEL: G10, G13, Q21, Q28

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1. Introduction

The European Union's Emissions Trading System (EU-ETS) is the largest cap-and-trade program yet implemented and has introduced emission allowances (EUA) as a new class of financial assets. Environmental policy has historically been a command-and-control type regulation where companies had to strictly comply with emission standards such that the trading scheme indicates a shift in paradigms. Under the Kyoto Protocol the EU had committed to reducing greenhouse gas (GHG) emissions by 8% compared to the 1990 level by the year 2012, while the proposed caps in the EU-ETS for 2020 represent a reduction of more than 20% of greenhouse gases. 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 lasted from 2008 to 2012. The third trading period started in January 2013 and will last until December 2020. Since its inception, the system has been significantly expanded in scope to include both new sectors and additional countries. It has evolved from a system with decentralized allocations based on national allocation plans towards a centralized system, featuring an EU-wide cap currently declining at an annual rate of 1.74%. For the second Kyoto commitment period (2013-2020), a high number of originally free allocations has also been replaced by a combination of auctioning, with full auctioning for all participating sectors as the long-term goal. Failure to submit a sufficient amount of allowances has also resulted in increased sanction payments from 40 Euro during the pilot trading period to 100 EUR per missing ton of CO_2 allowances during the second and third trading period (Chevallier, 2012; Hintermann, 2010).

Emission allowances are typically classified as a new financial asset or as a so-called *pseudo-commodity* whose price reflects expectations regarding the evolution of the equilibrium in supply and demand Roncoroni (2015). Supply is determined by regulatory authorities through initial allocations of EUAs, banking and borrowing provisions for market participants and is also impacted by the amount of certified emission reductions (CERs) that can be converted into emission permits valid for compliance with the EU-ETS[1]. On the other hand, the demand side depends on the evolution of EUA price drivers that include long and short-term abatement options, energy prices, weather conditions and economic growth. Despite the specific features of the emission allowance market, since the introduction of exchanges for spot and futures contracts, the price behavior of CO_2 allowances has typically been analyzed in a way very similar to other commodities or financial assets, see, e.g., Benz and Trück (2008); Chevallier (2009a); Chesney and Taschini (2012); Crossland et al. (2013); Daskalakis et al. (2009); Gronwald et al. (2011); Hintermann (2010); Hitzemann et al. (2015); Paolella and Taschini (2008); Seifert et al. (2008).

The EU-ETS forces companies to hold an adequate number of allowances according to their carbon dioxide output, while participants face several risks specific to emissions trading. In particular, price risk and volume risk have to be considered. The former is due to the fluctuation of allowance prices, while the latter can be attributed to unexpected fluctuations in production figures and energy demand such that emitters do not know ex ante their exact demand for EUAs. Therefore, to hedge these risks, next to monitoring the spot market, also derivative instruments such as

[1] For a more thorough description and review of the EU-ETS as well as its relationship with the clean development mechanism (CDM) and CERs, we refer to, e.g., Chevallier (2012); Gronwald and Hintermann (2015); Roncoroni (2015).

options and futures contracts for carbon emission allowances are of great importance. Market participants face the decision when to buy additionally required permits or sell surplus allowances, in particular given the fact that since Phase II the scheme allows for the banking of surplus allowances and usage at a later stage. Therefore, in particular the relationship between carbon spot and futures prices will significantly impact on risk management and hedging decisions for participating companies (Chesney and Taschini, 2012; Daskalakis et al., 2009; Seifert et al., 2008).

In this study, we examine convenience yields in the EU-ETS during the first Kyoto commitment period (2008-2012), which has been found by Lucia et al. (2015) to be the most speculative EU-ETS phase to date. The connection between spot and futures prices as well as contango and backwardation market situations, have been thoroughly investigated for commodities like oil, electricity, gas or agricultural products, see, e.g., Bodie and Rosansky (1980); Chang (1985); Gibson and Schwartz (1990); Pindyck (2001); Schwartz and Smith (2000); Weron and Zator (2014), just to mention a few. As pointed out by these studies, the convenience yield is one of the key factors relevant for the pricing of commodity futures contracts and the understanding of risks and return in these markets. Given the importance and the substantial use of futures contracts in commodity markets[2], this is a crucial issue for producers, consumers and commodity investors alike.

Interestingly, in comparison to other commodity markets, the relationship between prices of spot and futures contracts and convenience yields in the EU-ETS have not been studied extensively. At the same time, as pointed out by, e.g., Benz and Hengelbrock (2008); Hitzemann et al. (2015); Lucia et al. (2015); Mizrach and Otsubo (2014), trading volume and liquidity in the CO_2 futures market have increased significantly over recent years, emphasizing the importance of futures contracts also for the trading of emission allowances. However, as shown by Crossland et al. (2013), despite its rapid evolution, the EU-ETS is not informationally efficient yet.

We are particularly interested in deviations from the cost-of-carry relationship in Phase II of the trading scheme, where banking of surplus allowances for usage in later periods was allowed. Such an analysis will provide us with information on existing risk premiums in the EU-ETS and will yield results on how much market participants are willing to pay for a hedge against the risk of price movements in the EUA market. Our analysis also aims to provide insights into the driving factors of convenience yields for carbon emission futures contracts. In particular, we examine the impact of interest rate levels in the Eurozone, surplus allowances and banking, and factors related to the dynamics and risk of EUA spot prices. Information on the impact of these factors does not only provide a better understanding of the determinants and empirical properties of convenience yields (Casassus and Collin-Dufresne, 2005; Bollinger and Kind, 2010; Prokopczuk and Wu, 2013), but will also provide insights that could be relevant for the recent literature on trading strategies and risk premiums in commodity futures markets (Gorton and Rouwenhorst, 2006; Miffre and Rallis, 2007; Chng, 2009; Rouwenhorst and Tang, 2012).

Our findings suggest that during Phase II the market has changed from an initial short period of backwardation to contango with substantial negative convenience yields in futures contracts. These results indicate a significant deviation from the cost-of-carry relationship for EUA spot and

[2]The growth in commodity investments via futures trading has recently led to a debate about the financialization of commodity markets, see, e.g., Stoll and Whaley (2010); Tang and Xiong (2012); Cheng and Xiong (2013); Henderson et al. (2015).

futures contracts. Our analysis also yields important insights into the key drivers of observed convenience yields in the EU-ETS. Clearly, interest rates are expected to have a significant impact on the relationship between commodity spot and futures prices. The risk-free rate has also been suggested as a pricing factor for commodity derivatives, see e.g. Casassus and Collin-Dufresne (2005); Schwartz (1997); Schwartz and Smith (2000). Since interest rates are typically also related to – or even considered to be a proxy for – economic activity, they might well be expected to affect convenience yields. Our findings suggest that the drop in risk-free rates during the financial crisis in 2008, and the subsequently low interest rate levels as a result of the European Sovereign Debt crisis, have had a significant impact on the relationship between spot and futures contracts during the first Kyoto commitment period.

We also examine the relationship between banking of surplus allowances in the EU-ETS and the observed convenience yields. The theory of storage suggests a negative relationship between the convenience yield and inventory (Pindyck, 2001), such that an increasing amount of surplus allowances, as reported by Ellerman et al. (2014) and Zaklan et al. (2014), is expected to reduce convenience yields. We find confirmation for this relationship with convenience yields becoming more negative as surplus allowances increase throughout the sample period.

Finally, we study how the behavior of EUA spot prices impacts on the relationship between spot and futures contracts. We examine the relationship between variables such as realized variance and skewness of spot allowance prices and observed convenience yields. Similar measures have been applied in studies on risk premiums in equity markets (Hwang and Satchell, 1999), foreign currency markets (Christiansen, 2011; Jiang and Chiang, 2000; Kumar and Trück, 2014) or electricity markets (Bessembinder and Lemmon, 2002; Botterud et al., 2010; Bunn and Chen, 2013; Redl et al., 2009; Weron and Zator, 2014). We find that increased price volatility in the EUA spot market decreases convenience yields, suggesting that market participants are willing to pay an additional premium in the futures market for a hedge against increased uncertainty in EUA prices.

Our study contributes to the literature in several dimensions. To the best of our knowledge, we provide the first study to consider the relationship between carbon emission spot and futures prices for the entire first Kyoto commitment period from 2008 to 2012. Also, unlike previous studies by Chang et al. (2013), Gorenflo (2013) and Madaleno and Pinho (2011), where an assumption about a constant average risk-free rate is made, we use actually observed daily risk-free rates for each maturity of the futures contracts to determine a more precise estimate of the convenience yield. We are also the first to thoroughly examine the impact of key factors such as interest rate levels, surplus allowances, and factors related to the dynamics of EUA spot prices on convenience yields and risk premiums in the EU-ETS. Our results provide important insights on the relationship between EUA spot and futures contracts and the drivers of convenience yields in this unique market.

The remainder of the paper is organized as follows. Section 2 provides a review of the literature related to this study, namely on the analysis of EUA spot and futures contracts and convenience yields and risk premiums in other commodity markets. Section 3 reviews general concepts about the relationship between spot and futures prices in commodity markets and explains the rationale of normal backwardation or contango markets. It further illustrates the idea of the convenience yield as the benefit to the holder of commodity inventory. Section 4 provides our empirical analysis on CO_2 spot and futures prices, estimated convenience yields and the relationship between the identified driving factors and the yields. Section 5 concludes and makes suggestions for future work.

2. Literature

Since the official start of spot and futures trading in 2005, researchers have investigated the price behavior of CO_2 allowances. Benz and Trück (2008), Paolella and Taschini (2008) as well as Seifert et al. (2008) were among the first studies to provide an econometric analysis of the behavior of allowance prices and investigate different models for the dynamics of short-term spot prices. Another stream of literature is more concerned with the price drivers of allowance markets, like macroeconomic conditions (Bredin and Muckley, 2011; Chevallier, 2009a), marginal abatement costs (Hintermann, 2010), yearly compliance events (Chevallier, 2011), other commodities, equity and energy indices (Gronwald et al., 2011), and announcements regarding decisions of the European Commission on National Allocation Plans (Conrad et al., 2012). Kanamura (2015) examines the impact of energy prices and EUA-CER swap transactions on volatility in the EUA market.

Some authors have focused on price discovery in CO_2 spot and futures markets. But the conclusions they reached are at times contradictory. For instance, Milunovich and Joyeux (2010) and Niblock and Harrison (2012) find that spot and forward prices both contribute jointly to price discovery in carbon markets, while Gorenflo (2013) and Uhrig-Homburg and Wagner (2009) conclude that the futures market has a leadership position against the spot market and contributes the most to price discovery. Analyzing futures markets only, Benz and Hengelbrock (2008) report that the more liquid market (ECX) is leading the less liquid market (Nord Pool). Finally, a few studies have provided insights on the pricing of vanilla and exotic derivative instruments written on the EUAs, see, e.g., Carmona and Hinz (2011); Chesney and Taschini (2012); Daskalakis et al. (2009); Isenegger et al. (2013); Kanamura (2012).

So far less attention has been directed towards the relationship between EUA spot and futures prices, convenience yields and deviations from the cost-of-carry relation in the EU-ETS. Exceptions include the studies by Chang et al. (2013); Chevallier (2009b); Gorenflo (2013); Madaleno and Pinho (2011); Milunovich and Joyeux (2010); Uhrig-Homburg and Wagner (2009); Trück et al. (2015) that are highly related to the work conducted in this paper. In the following we will briefly review the findings and some of the limitations of these studies.

Milunovich and Joyeux (2010) examine the issues of market efficiency 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, Uhrig-Homburg and Wagner (2009), also examining EUA prices during the pilot trading period, find contradictory results: examining the relationship between EU carbon spot and futures markets during Phase I, the authors 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. 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.

Chevallier (2009b) investigates the modeling of the convenience yield in the EU-ETS for the first year of Kyoto commitment period in 2008, using daily and intra-daily 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. Madaleno 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. More recently, Gorenflo (2013) suggests that the cost-of-carry hypothesis between spot and futures prices holds for the trial period while for the Kyoto commitment period there are deviations from the cost-of-carry relationship. Chang et al. (2013), based on the cost-of-carry model, examine the properties of convenience yields for CO_2 emissions allowances futures contracts with maturities from December 2010 to December 2014. The authors suggest that convenience yields for CO_2 emissions allowances exhibit a time-varying trend, are mean-reverting, while the standard deviation in the convenience yield declines with an increase in time-to-maturity. Note that unlike Chang et al. (2013), Gorenflo (2013) and Madaleno and Pinho (2011), where an assumption about a constant average risk-free rate is made, in our analysis we use the actually observed daily risk-free rates for each maturity to obtain more precise estimates of the convenience yield. Finally, Trück et al. (2015) investigate the relationship between spot and futures prices within the EU-ETS during the pilot trading and first Kyoto commitment period. They investigate price behavior, volatility term structures and correlations in EUA spot and futures contracts. Their findings suggest that during Phase II the market has changed from initial backwardation to contango. However, their analysis is mainly descriptive and does not examine the impact of interest rates, the level of surplus allowances and banking as well as returns, variance or skewness in the EU-ETS spot market on observed convenience yields.

Overall, due to the peculiarity of the market for CO_2 emission allowances as well as the ambiguous results on existing convenience yields in different commodity markets (Bierbrauer et al., 2007; Bodie and Rosansky, 1980; Botterud et al., 2010; Chang, 1985; Longstaff and Wang, 2004; Pindyck, 2001; Wei and Zhu, 2006; Weron, 2008; Weron and Zator, 2014), it seems worthwhile to compare more thoroughly the pricing relationship between EUA spot and futures prices. Also, while there have been a number of studies focusing on the dynamics of EUA spot prices, drivers of CO_2 allowance prices and the pricing of derivative contracts, so far only limited work on convenience yields and deviations from the cost-of-carry relationship in the EU-ETS has been conducted. As mentioned before, to the best of our knowledge in this paper we provide the first empirical analysis of the relationship between spot and futures prices, using data for the entire Phase II from 2008 to 2012. We also provide a pioneer study on examining the most important factors and their impact on the dynamics of observed convenience yields in the EU-ETS.

3. Emission Allowances and the Convenience Yield

Approaches for the valuation of forward and futures contracts can be conceptually divided into two groups (Fama and French, 1987; Geman, 2005; Weron, 2006). 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-of-carry relationship and the convenience of holding inventories. In the following we follow the second approach and briefly illustrate the derivation of the convenience yield.

The rationale for such an approach stems from the fact that EUAs can be treated as a factor of production (Benz and Trück, 2006; 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. The obvious parallels to a factor of production motivate the idea to adopt approaches from commodity markets (i.e. the convenience yield) rather then using typical financial models for asset pricing (i.e. the risk premium).

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).

Let S_t be the spot price of a commodity asset at time t and $F_{t,T}$ be the futures price of the asset at time t with maturity T. The cost-of-carry model describes an arbitrage relation between the futures price, spot price and the cost of carrying the asset. Then, with zero cost of storage as it is the case for EUA contracts, the no-arbitrage cost-of-carry relationship between the two assets can simply be expressed by:

$$F_{t,T} = S_t e^{r_{T-t}(T-t)} + \epsilon_{t,T}, \tag{1}$$

where r_{T-t} denotes the risk-free rate at time t referring to a time period $T - t$.

This relationship does not hold in most commodity markets, what can partly be attributed to the inability of investors and speculators to short the underlying asset S_t. Instead, the literature usually suggests a correction to the cost-of-carry pricing formula that includes the convenience yield:

$$F_{t,T} = S_t e^{(r_{T-t} - c_{T-t})(T-t)}, \tag{2}$$

where c_{T-t} refers to the convenience yield observed at time t referring to a time period $T - t$, i.e. for a futures contract with maturity at T. Solving for c_{T-t}, we get the following equation for the convenience yield:

$$c_{(T-t)} = r_{T-t} - \frac{\ln(F_{t,T}) - \ln(S_t)}{T - t}. \tag{3}$$

As mentioned above, 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. Alternatively, one could argue that the convenience yield is the *residual* needed to align cost-of-carry commodity futures prices with observed market prices.

At time t, the futures price $F_{t,T}$ of a commodity with delivery in T can be greater, equal or less than the current spot price of the asset S_t. Further, it can also be greater or less than the expected spot price $E_t(S_T)$ at delivery T. 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 (see e.g. Geman, 2005; Hull, 2005).

The differences between spot and futures prices can be explained by a typical insurance contract: in the (normal) backwardation case, 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* can be seen as a drift adjustment (a constant – λ, a deterministic function of time – λ_t) in the stochastic differential equation (SDE) governing the spot price dynamics to reflect how investors are compensated for bearing risk when holding the spot (Weron and Zator, 2014). In other words, the drift adjustment when moving from the original 'risky' probability measure P to the 'risk-neutral' measure P^λ, like in the Black-Scholes-Merton model (Hull, 2005). Although different in value, a constant market price of risk is of the same sign as the risk premium.

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 commodity asset classes, 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) and more recently Haugom and Ullrich (2012) 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 and over the years. Botterud et al. (2010) and Weron (2008) find negative (on average) risk premiums in Nord Pool electricity Asian options and futures prices, but in a more recent study Weron and Zator (2014) report that both risk premiums and convenience yields vary significantly over time. In particular, for shorter maturities (i.e. 1 week) risk premiums are typically positive on average, while for longer maturities (i.e. 6 weeks) they are negative. Bierbrauer et al. (2007) and Haugom et al. (2014) obtain similar results for medium-term futures contracts examining prices from the EEX and Nord Pool markets, respectively. 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.

For EUAs, Madaleno and Pinho (2011) 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. Gorenflo (2013) suggests that the cost-of-carry hypothesis between spot and futures prices holds for the trial period, while for the Kyoto commitment period there are deviations from the cost-of-carry relationship. Chang et al. (2013) suggest that convenience yields for Phase II and III futures contracts exhibit a time-varying trend, are mean-reverting, while the standard deviation in the convenience yield declines with an increase in time-to-maturity. Most recently, Trück et al. (2015), analyzing the behavior of CO_2 spot and futures contracts, find that during Phase II the market has changed from initial backwardation to contango with significant negative convenience yields. However, none of the above-mentioned studies does relate the dynamics of observed convenience yields to explanatory variables such as interest rate levels, the banking of surplus allowances or the volatility of EUA spot prices.

4. Empirical Results

4.1. The Data

Data spot and futures prices is sourced from PointCarbon, one of the major data suppliers for global gas, power and carbon markets. We consider Bluenext spot and European Climate Exchange (ECX) futures prices for the first Kyoto commitment period from April 8, 2008 to December 31, 2012.[3]. 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. During the considered period, futures contracts referring to both Phase II (2008-2012) and Phase III (2013-2020) were traded. In total we consider seven different futures contracts, four of them referring to an expiry data during the first Kytoto commitment period (2009, 2010, 2011, 2012), three of them referring to the second Kyoto commitment period beginning on January 1, 2013 (contracts with expiry in 2013, 2014 and 2015). The contract volume amounts to 1000 tons of CO_2 and the contracts expire on the last business day in December. 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. Delivery of EU emission allowances is carried out up to two business days after maturity of the contracts.

For the risk-free rates we use daily European Central Bank (ECB) quotes for AAA-rated euro area central government bonds. These quotes are available for bonds with a maturity from 3 months up to 5 years. To match the yields for different time horizons until maturity of the considered futures contracts, we use linear interpolation. Note that unlike the studies by Chang et al. (2013), Gorenflo (2013) and Madaleno and Pinho (2011), where an assumption about a constant average risk-free rate is made, we use the actually observed daily rates for each maturity.

4.2. Convenience Yields

Let us now examine the relationship between spot and futures contracts for the time period April 8, 2008 to December 31, 2012. Figure 1 provides the spot price series as well as December 2010, 2012 and 2014 futures price for the period considered.[4] We observe that the Phase II EUA spot price (bold solid line) on April 8, 2008 was EUR 23.53 and initially increased to its maximum level of EUR 29.38 on July 1, 2008. What followed was a relatively rapid decline in prices down to EUR 8.00 on February 12, 2009 which can mainly be attributed to the impacts of the financial crisis and lower expectations about economic output in the Eurozone due to the crisis. Spot prices increased again up to a level of EUR 15.45 in May 2009 and remained in the range EUR 13–16 up to June 2011. Since then, due to the European Sovereign Debt crisis, expectations about lower economic output and emissions below the actual annual allocation of allowances, prices dropped to a level of approximately EUR 6.50 in December 2012. We also observe that spot and futures prices show a similar price behavior during the considered time period.

[3]These exchanges were chosen, since they provide a high level of liquidity, see, e.g. Mizrach and Otsubo (2014).

[4]Note that the 2010 futures contract expired on December 20, 2010, the 2012 futures contract on December 17, 2012, while the first price observation for the 2014 futures contract was available on December 21, 2010.

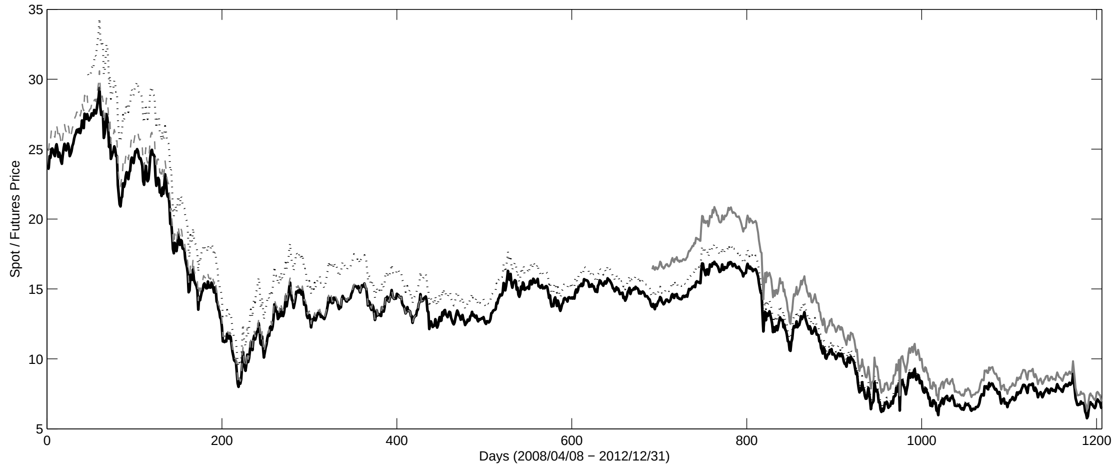

Figure 1: Spot price (solid black), December 2010 (dashed), December 2012 (dotted) and December 2014 (solid grey) futures price for the first Kyoto commitment period April 8, 2008 to December 31, 2012. The December 2010 futures contract expired on December 20, 2010, the December 2012 futures contract on December 17, 2012, while the first price observation for the 2014 futures contract was available on December 21, 2010.

The co-movement of spot and futures contracts during the first Kyoto commitment period is also confirmed by looking at the correlation coefficients between returns from spot and considered futures contracts in Table 1. We find that correlations between spot and futures returns are all well above 0.95 and close to one. This is also true for futures contracts referring to Phase III, although correlations between Phase II spot and futures returns and the 2015 futures contracts are slightly lower than for most of the other contracts.

In a next step, using equation (3) we calculate convenience yields for the 2009-2015 futures contracts. Summary statistics for the estimated convenience yields are reported in Table 2. We find negative average convenience yields for all futures contracts, while the absolute value of the yields increases for contracts with longer maturities. While for Phase II futures contracts the mean of observed convenience yields has a range between roughly -1% for the 2009 contract and -2.14% for the 2012 contract, for Phase III average convenience yields are between -3.68% for the 2013 contract and -5.03% for the 2015 contract. Clearly, for Phase III the market indicates substantial negative convenience yields, in magnitude well above the level of the risk-free rate, such that $(r_{T-t} - c_{T-t}) > 0$ and, therefore, Phase III futures prices are typically significantly higher than the spot. This behavior is also illustrated in Figure 1, where the relatively large deviation of 2014 futures prices from the spot price is displayed. Interestingly, we also find that the standard deviation of convenience yields decreases for longer maturity of the futures contract. It is the highest for the convenience yield of the nearest term 2009 futures ($\sigma = 0.0156$) and by far the lowest for the 2015 futures contract ($\sigma = 0.0057$). These results are in line with the proposed time-to-maturity or Samuelson effect for commodity markets (Samuelson, 1965) that suggests a typically declining term structure in the volatility of futures prices as maturity increases. The behavior is generally explained by the fact that only few of the parameters affecting the opinion of investors about distant futures prices will change today. Hence, only minor effects are expected

Delivery	Spot	2009	2010	2011	2012	2013	2014	2015
Spot	1.0000	0.9915	0.9809	0.9708	0.9689	0.9897	0.9888	0.9580
2009		1.0000	0.9895	0.9797	0.9794	-	-	-
2010			1.0000	0.9870	0.9779	0.9784	-	-
2011				1.0000	0.9774	0.9863	0.9819	-
2012					1.0000	0.9955	0.9944	0.9626
2013						1.0000	0.9970	0.9667
2014							1.0000	0.9680
2015								1.0000

Table 1: Correlations between returns from spot and 2009-2015 futures contracts for Kyoto commitment period market quotes from April 8, 2008 to December 31, 2012. Note that correlation coefficients between returns from the 2009 and 2013, 2014 and 2015 futures contracts could not be calculated because the 2009 contract expired before quotes for these contracts were available. The same is true for the correlation coefficient between 2010 and 2014, 2015 contracts and for 2011 and 2015 futures contracts.

Contract	2009	2010	2011	2012	2013	2014	2015
Mean	-0.0099	-0.0107	-0.0144	-0.0214	-0.0368	-0.0435	-0.0503
Median	-0.0116	-0.0125	-0.0152	-0.0205	-0.0346	-0.0447	-0.0508
Std	0.0156	0.0121	0.0114	0.0120	0.0112	0.0112	0.0057
Min	-0.0417	-0.0506	-0.0636	-0.0626	-0.0737	-0.0661	-0.0633
Max	0.0307	0.0285	0.0264	0.0230	-0.0204	-0.0200	-0.0303
Obs	411	670	924	1131	773	515	261

Table 2: Descriptive statistics for convenience yields for 2009 - 2015 futures contracts. The 2009 futures contract expired on December 14, 2009, the 2010 futures contract expired on December 20, 2010, the 2011 contract on December 19, 2011 and the 2012 contract on December 17, 2012. Phase III futures contract prices were available from December 16, 2009 (2013 futures), December 21, 2010 (2014 futures) and December 20, 2011 (2015 futures).

for futures with long maturities, even if there are more significant changes to the spot price or near-term futures contracts.

Figure 2 provides a plot of the observed convenience yields for the December 2009, 2011 and 2012 futures contracts based on the cost-of-carry relationship described in Section 3. We observe that 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. In the course of time, the market situation changed from backwardation to contango for the first time in July 2008. Prices were approximately in line with the cost-of-carry relationship until end of October 2008, but afterwards convenience yields become negative. For most of the time after January 2009, convenience yields for the 2010, 2011 and 2012 futures contracts are significantly smaller than zero. Thus, we find that 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 maturities, i.e. the December 2011 and 2012 futures contracts. We also observe that as the contracts get closer to the expiry date, the convenience yield becomes more volatile.

Figure 3 displays the results for the relationship between Phase II spot and Phase III futures

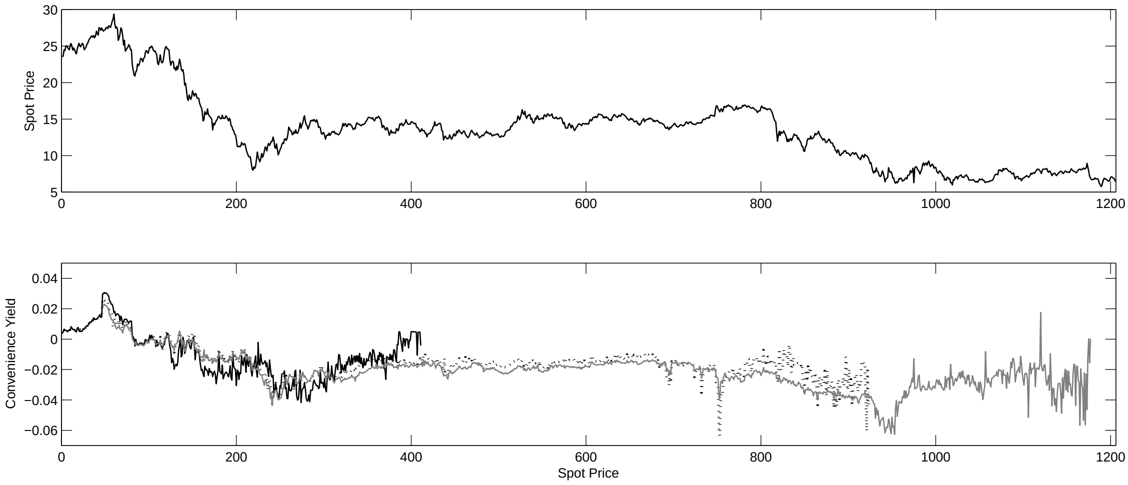

Figure 2: *Upper panel:* Spot prices (EUR/ton) from April 8, 2008 to December 31, 2012. *Lower panel:* Convenience yields (EUR/ton) for 2009 (solid black), 2011 (dashed black) and 2012 (solid grey) EUA futures contracts. The 2009 futures contract expired on December 14, 2009, the 2011 contract on December 19, 2011 and the 2012 contract on December 17, 2012.

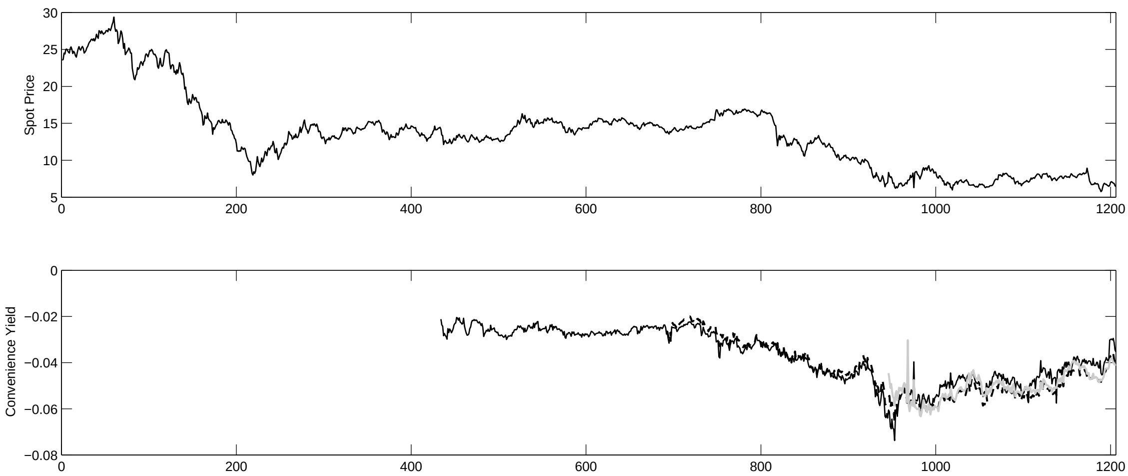

Figure 3: *Upper panel:* Spot prices (EUR/ton) from December 16, 2009 to December 31, 2012. *Lower panel:* Convenience yields (EUR/ton) for December 2013 (solid black), December 2014 (dotted black) and December 2015 (solid grey) EUA futures contracts. Phase III futures contract prices were available from December 16, 2009 (2013 futures), December 21, 2010 (2014 futures) and December 20, 2011 (2015 futures).

contracts. Note that inter-period banking between the phases is allowed such that the EU-ETS enables market participants to use Phase II permits also during Phase III. On the other hand, borrowing of permits from Phase III and using the allowances in Phase II is not allowed. Prices for the considered Phase III futures contracts were only available from December 16, 2009 (2013 futures), December 21, 2010 (2014 futures) and December 20, 2011 (2015 futures). Therefore, the lower panel of Figure 3 only provides a plot of the convenience yields for this time period. We find highly negative convenience yields for all Phase III futures contracts, usually in the range between -2% and -7%. In the year 2012, observed convenience yields have been reduced in magnitude, however, they remain below -2% for all contracts during the entire time period.

Note that our findings with respect to a clear deviation from the cost-of-carry relationship for Phase II are in line with earlier work examining EUA spot and futures contracts during the Kyoto commitment period (Chang et al., 2013; Gorenflo, 2013; Madaleno and Pinho, 2011; Trück et al., 2015). However, the consistently negative sign of observed convenience yields from March 2009 onwards, at least partially contradicts results reported in some of these studies. Madaleno and Pinho (2011) and Chang et al. (2013) report positive convenience yields during late 2009 and 2010 for some of the futures contracts (usually contracts with maturity during Phase II, i.e. expiry in December 2010, 2011 or 2012). The key reason for the deviation in our results, may be different assumptions about the risk-free rate. While Madaleno and Pinho (2011) assume a constant interest rate for the estimation period of 4%, Chang et al. (2013) choose a constant free-risk rate equal to the average coupon rate of 3.06%, i.e. the rate for three-year government bonds issued in 2010 in the European Union. Also Gorenflo (2013) state that the interest rate is assumed to be constant over time in his analysis. Note that in our study we do not assume a constant risk-free rate, but decided to use actual daily European Central Bank (ECB) quotes for AAA-rated euro area central government bonds for different maturities. Further, to match the yields for different time horizons until maturity of the considered futures contracts we use linear interpolation between quoted interest rates. As mentioned earlier, risk-free rates in the Eurozone have dropped significantly from a level of around 4% in September 2008 to a level below 1% since late September 2009. Therefore, it is no surprise that in our analysis we obtain different results in comparison to previous studies, where significantly higher interest rates have been applied.

Overall, the negative convenience yields for Kyoto period futures contracts from 2009 onwards indicate that market participants saw no privilege in holding the allowance now with respect to future periods. We find that long positions in futures contracts are priced at a much higher level than suggested by the cost-of-carry relationship. Generally, a contango market as it is observed during Phase II would suggest currently available supply but potential medium-to-long-term shortages of a commodity. Under such a scenario, consumers might be interested in buying insurance against rising prices in the futures market. Therefore, a greater interest in long futures positions will drive prices of these contracts up. Observed negative convenience yields may be interpreted as consumers' willingness to pay an additional risk premium for a hedge against rising prices or future shortage of EUAs. Clearly, it can also be interpreted as a hedge against potential changes in regulation that may reduce the availability of permits in forthcoming years.

As banking and borrowing within the years of the Kyoto commitment period (i.e. 2008-2012) is allowed, one could also argue that the deviation from the cost-of-carry relationship may be due to different market expectations about interest rates in forthcoming years. Although firms tend to

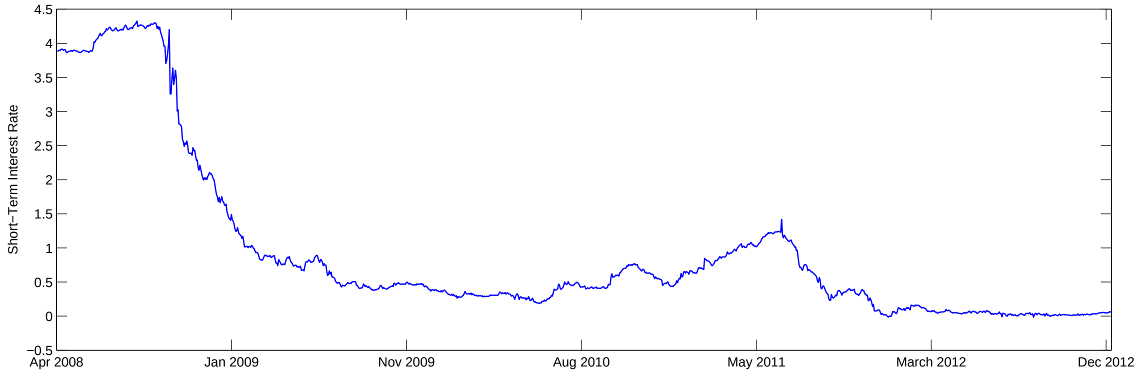

Figure 4: Daily short term (3-month) European Central Bank (ECB) quotes for AAA-rated Euro area central government bonds from April 8, 2008 to December 31, 2012.

use banking provisions in a rational way, as reported by Ellerman and Montero (2007) for the US Acid Rain Program, the increasing surplus levels and banking of EUAs might suggest expected relatively low scarcity of the allowances at time t versus some time in the future T, i.e. the maturity of the futures contracts. This encourages us to analyze the behavior of observed convenience yields with regards to possible drivers of the yields in more detail.

4.3. Driving factors of the Convenience Yield

In the following, we try to explain the observed deviations from the cost-of-carry relationship by a number of exogenous variables. In particular we attribute the existence of negative convenience yields of relatively high absolute magnitude to the following factors: (i) interest rate levels in the Eurozone, (ii) the increasing level of surplus allowances and banking during Phase II, and (iii) market participants' willingness to pay an additional risk premium for a hedge against uncertainty about EUA price behavior and possibly rising prices in future periods.

4.3.1. Interest Rates

The first reason for observing negative convenience yields may be the extremely low risk-free rates in the Eurozone from 2009 onwards. The drop of the risk-free rate from roughly 4% in early 2008 to a rate near 0.5% from January 2009 onwards was initially due to the global financial crisis, while yields for AAA-rated government bonds have remained at such low levels ever since. Interest rates can be expected to impact on the relationship between commodity spot and futures prices and have been suggested as a pricing factor for commodity derivatives, see e.g. Casassus and Collin-Dufresne (2005); Schwartz (1997); Schwartz and Smith (2000). Note that in the three-factor model developed by Casassus and Collin-Dufresne (2005), the convenience yield can be dependent on the risk-free rate itself. As indicated by equations (3) and (4), the risk-free rate is also a key input in the cost-of-carry model and, therefore, will have an impact on deviations from this relationship and the calculation of the convenience yield. We also observe that convenience yields become more significant once risk-free rates in the Eurozone drop to the low levels observed since 2009. During periods of very low interest rates it may be more likely to observe negative convenience yields for risky assets. This could be a result of market expectations about rising interest rates in forthcoming periods. We use daily short term (3-month) European Central Bank (ECB) quotes for AAA-rated Euro area central government bonds as a proxy for the risk-free spot rate in our analysis. Figure 4 provides a plot of the interest rate applied in the analysis. We formulate the following hypothesis about the relationship between the risk-free rate and convenience yields in the EU-ETS:

Hypothesis 1: *Lower interest rates will decrease the convenience yield, such that we expect a positive relationship between interest rates and observed convenience yields.*

Based on *Hypothesis 1*, we would therefore expect a positive coefficient, when regressing convenience yields on short-term interest rates.

4.3.2. Banking

The second explanation refers to the possibility of banking EUAs and the surplus of allowances available during Phase II. Generally, the theory of storage suggests a negative relationship between the convenience yield and inventory, see e.g. Pindyck (2001). The owner of a commodity, who is free to consume it until maturity, is prepared for unexpected shortages in supply or increases in demand. The convenience yield then represents this additional benefit of holding a unit of inventory, for instance, to be able to meet unexpected demand. The value of this benefit should then be negatively related to the level of inventory. One could argue that it is particularly high if inventories of a commodity are low and consumers are forced to secure a short-term supply. On the other hand, high levels of inventory will reduce the benefits and, therefore, also the convenience yield. Considering the continuously increasing level of surplus allowances during the first Kyoto commitment period (Ellerman et al., 2014; Zaklan et al., 2014) and the extensive use of external credits coming from two of the Kyoto Protocol mechanisms, the clean development mechanism (CDM) and joint implementation (JI), one could argue that throughout Phase II an increasingly higher level of inventory was accumulated.[5] Therefore, the change in the market from backwardation to contango and significantly negative convenience yields for futures contracts could be a result of an increasing level of surplus allowances and banking. We formulate the following hypothesis about the relationship between surplus allowances and observed convenience yields:

Hypothesis 2: *An increase in the number of surplus allowances will decrease the benefit of holding spot contracts in comparison to a position in a futures contract. Thus, we expect a negative relationship between the EUA bank and observed convenience yields.*

Data on allowance banking behavior are available in the European Union Transaction Log (EUTL) and comprise installation-level information on free allocations, verified emissions and surrenders of both EUAs and Kyoto offsets against emissions (Zaklan et al., 2014). Note that in order to compute the correct size of the bank at a sub-system level, we would also require information on sales and purchases of EUAs. Unfortunately, for this level of detail, data are not available until

[5] See also http://europeanclimatepolicy.eu/.

Year	2008	2009	2010	2011	2012
Allocation	1,950,775	1,966,046	1,990,089	2,008,498	2,218,785
Emissions	2,100,311	1,860,378	1,919,639	1,885,373	1,929,554
Offset	83,379	80,299	133,782	251,368	500,704
EUA Bank	-66,157	119,811	324,043	698,535	1,488,680

Table 3: Aggregate free allocations, verified emissions and surrenders of both EUAs and Kyoto offsets against emissions and aggregate surplus levels (EUA bank) for Phase II at the end of 2008, 2009, 2010, 2011 and 2012.

several years later. However, since purchases and sales cancel each other out at the aggregate level, the correct size of aggregate EUA surplus levels can be calculated without requiring information on transfers. Table 3 provides figures for aggregate free allocations, verified emissions and surrenders of both EUAs and Kyoto offsets against emissions as well as the aggregate EUA bank for Phase II. Note that this information is only available at annual frequency for the end of 2008, 2009, 2010, 2011 and 2012, such that we use linear interpolation to determine EUA surplus allowance levels at higher frequency.[6] Table 3 clearly illustrates that after an initially negative EUA bank by the end of 2008, the number of surplus allowances has been significantly increasing with approximately 700,000, respectively 1,500,000, surplus allowances reported by the end of 2011 and 2012.

4.3.3. Spot Market Volatility and Skewness

The significantly negative convenience yields for Phase II and Phase III futures contracts indicate that long positions in futures contracts are priced above price levels suggested by the cost-of-carry relationship. As mentioned earlier, one may interpret this as consumers' willingness to pay an additional risk premium for a hedge against rising prices or shortage of EUAs in future periods.

Typical measures for risk and uncertainty about price movements in a financial market are the volatility or skewness of returns in the spot market. To include such measures for risk is also motivated by various studies on the relationship between spot and futures prices in other markets. For equity markets, e.g. Hwang and Satchell (1999) suggest to examine the relationship between risk premiums in the forward market and skewness and kurtosis in equity markets for emerging economies, while Jiang and Chiang (2000) examine the influence of currency and stock market volatility on forward premiums. For currency markets, Christiansen (2011) and Kumar and Trück (2014) find evidence for inter-temporal risk-return trade-off of foreign exchange rates and futures risk premiums being driven by explanatory variables such as realized variance, skewness and kurtosis for currency spot returns.

For electricity markets, Bessembinder and Lemmon (2002) suggest that risk premiums of forward contracts can be related to the variance and skewness of spot prices in electricity markets. The model has been tested in various applications to electricity markets all over the world, providing mixed evidence for the impact of variance and skewness of electricity spot prices on risk premiums in the forward market, see e.g. Bunn and Chen (2013); Handika and Trück (2013); Haugom and Ullrich (2012); Torro and Lucia (2011); Redl et al. (2009), just to name a few. Bot-

[6]In our analysis we also used different approaches to interpolation, for example a cubic spline. However, the method of interpolation did not change the sign or significance of the estimated coefficients.

terud et al. (2010) and Weron and Zator (2014) investigate convenience yields in the Nord Pool electricity market and find a significant relationship between the yields and spot price variance and skewness. For the relationship between EUA spot and futures contracts, Chevallier (2009b) and Madaleno and Pinho (2011) also regress observed convenience yields on measures of volatility in the spot market. However, their analysis is limited to either data from the pilot trading period only or observations up to 2009.

Motivated by this line of research, we examine the impact of volatility and skewness in the EUA spot market on the observed convenience yields during the first Kyoto commitment period. We apply an exponentially weighted moving average (EWMA) to model the volatility in the EUA spot market, where the variance estimate σ_t^2 for returns in the EUA spot market for day t is based on the following relationship:

$$VAR_t \equiv \sigma_t^2 = \lambda\sigma_{t-1}^2 + (1-\lambda)r_{t-1}^2, \tag{4}$$

with σ_{t-1}^2 being the previous day's estimate for the variance and r_{t-1}^2 the square of the most recent EUA return observation.[7] The estimated variance at each point in time is then used as an explanatory variable for the observed convenience yields. We formulate the following hypothesis about the relationship between variance in the EUA spot market and the convenience yields:

Hypothesis 3: *Increased variance in the spot market, will increase the demand for hedging and, therefore, increase futures prices. Thus, we expect a negative relationship between spot market volatility and observed convenience yields.*

4.4. The Convenience Yield Models

In the following we will describe the results for the applied models for the dynamics of the observed convenience yields. Recall that due to expiry of the futures contracts and a later start of trading for some of the Phase III contracts, we do not observe prices for all contracts throughout the entire sample period (April 8, 2008 - December 31, 2012). For example, the 2009, 2010 and 2011 futures contracts expired at least a year before the end of the sample period, while prices for the 2014 futures contract were only available from December 21, 2010.[8] Therefore, we have an unbalanced data set, where convenience yields for contracts $i = 1, ..., 7$ are observed different number of times T_i. Hereby $i = 1$ refers to the 2009 futures contract, $i = 2$ to the 2010 futures contract and so on.

We first investigate the dynamics of the convenience yields using a pooled OLS estimator (*Model I*)

$$\mathrm{CY}_{i,t} = \beta_0 + \beta_1\mathrm{INT}_t + \beta_2\mathrm{BANK}_t + \beta_3\mathrm{VAR}_t + \epsilon_{i,t}, \tag{5}$$

[7]We use $\lambda = 0.94$ for the smoothing parameter, following the approach suggested in RiskMetrics^{TM}. Note that we also applied alternative values for the smoothing parameter λ as well as a GARCH(1,1) model for the conditional volatility of EUA returns. However, the different approaches did not change the sign and significance of the estimated coefficients in the applied regression models and gave very similar results.

[8]See Table 2 for details on trading dates and the number of observations on convenience yields for each of the 2009-2015 futures contracts.

where INT_t denotes the short term (3-month) interest rate in the Eurozone area at time t, BANK_t is an estimate of the number of EUA surplus allowances at time t, VAR_t is the estimated volatility in the EUA spot market at time t based on the applied EWMA model, see equation (4), and $\epsilon_{i,t}$ is the noise term, assumed to be independent and identically distributed with mean zero and finite variance.

As mentioned above, the literature (Bessembinder and Lemmon, 2002; Christiansen, 2011; Kumar and Trück, 2014) suggests that also returns in the spot market as well as higher moments of spot price returns may have an impact on risk premiums in the futures markets. These risk premiums would then also be reflected in observed convenience yields for CO_2 futures contracts. Therefore, we also apply an extended model, where we include the estimated skewness SKEW_t and the most recent return r_t in the EUA spot market at time t. To model skewness we apply a rolling estimator based on the last k daily returns:

$$\text{SKEW}_t = \frac{1}{k-1} \sum_{i=1}^{k} \frac{(r_i - \bar{r})^3}{\sigma_t}, \tag{6}$$

where σ_t denotes the standard deviation and $\bar{r}$ the average of EUA spot returns during the last k trading days. We choose $k = 20$ what roughly corresponds to the skewness of returns in the EUA spot market during the last month and formulate the following extended model (*Model II*):

$$\text{CY}_{i,t} = \beta_0 + \beta_1 \text{INT}_t + \beta_2 \text{BANK}_t + \beta_3 \text{VAR}_t + \beta_4 \text{r}_t + \beta_5 \text{SKEW}_t + \epsilon_{i,t}. \tag{7}$$

Note, however, that given the substantial differences between the magnitude of observed convenience yields for the 2009-2015 contracts (see Table 2), the assumption of a common constant term for all contracts in *Model I* and *Model II* may not be appropriate. Recall that for Phase III futures contracts, we found the convenience yields far more pronounced (in absolute terms) in comparison to Phase II contracts. To further investigate this issue, we also run the pooled regression with additional dummy variables to distinguish between individual future contracts.

First, we consider a model that distinguishes between futures contracts with expiry date in Phase II and Phase III, by introducing a dummy variable $d_{phaseIII}$ with $d_{phaseIII} = 1$ for observations for contracts $i = 5, 6, 7$.

Thus, *Model III* becomes

$$\text{CY}_{i,t} = \beta_0 + \beta_1 \text{INT}_t + \beta_2 \text{BANK}_t + \beta_3 \text{VAR}_t + \gamma d_{phaseIII} + \epsilon_{i,t}, \tag{8}$$

while in *Model IV* we simply include the Phase III dummy variable into the equation for *Model II*.

We also consider a model with separate dummy variables for the individual contracts to further address heterogeneity in the convenience yields for the traded EUA futures. Thus, we define $d_i = 1$ for observations of futures contracts $i = 2, 3, ..., 7$ and $d_i = 0$ otherwise. To avoid the 'dummy variable trap', no dummy is used for the 2009 contract ($i = 1$). Thus, the model including dummy variables for the individual contracts (*Model V*) takes the following form:

$$\text{CY}_{i,t} = \beta_0 + \beta_1 \text{INT}_t + \beta_2 \text{BANK}_t + \beta_3 \text{VAR}_t + \sum_{i=2}^{7} \gamma_i d_i + \epsilon_{i,t}. \tag{9}$$

Then running the pooled OLS regression, $\hat{\gamma}_2$ denotes the coefficient on d_2, $\hat{\gamma}_3$ is the coefficient on d_3, and so on. Note that this model is typically referred to as the *dummy variable regression* and the estimators for $\beta_1, \beta_2, \beta_3$ will be identical to the fixed effects estimators, see, e.g. Wooldridge (2010). It is straightforward to also include the contract dummy variables into the extended *Model II*, what yields *Model VI*.

Results for the considered six models are provided in Table 4. We report estimated coefficients as well as Newey-West HAC adjusted standard errors to account for autocorrelation and heteroskedasticity in the explanatory and dependent variables.

Examining the results for the most basic *Model I*, see equation (5), we observe that all estimated coefficients are significant at the 1% level and show the expected signs according to *Hypothesis 1-3*. The relationship between interest rates and convenience yields is positive, suggesting that the drop in risk-free rates during the financial crisis period and the subsequent low interest rate environment has also had a significant impact on convenience yields in the EU-ETS futures market. We also find evidence for the negative relationship between the convenience yield and inventory as it has been suggested in the theory of storage, confirming *Hypothesis 2*. Thus, the rising number of surplus allowances throughout the sample period has led to a further decrease in convenience yields for EUA futures. Furthermore, we find a significant negative relationship between the variance of spot prices and convenience yields. Therefore, increased price volatility in the EUA spot market will decrease convenience yields, indicating that market participants are willing to pay an additional risk premium in the futures market for a hedge against increased uncertainty about EUA prices. We also find that the simple specification of *Model I* provides a relatively high explanatory power of $R^2 = 0.721$, suggesting more than 70% of the variation in convenience yields for the futures contracts can be explained by the proposed variables.

Comparing these results to *Model II*, see equation (7), we observe that including additional variables capturing the most recent return in the EUA spot market as well as a measure for skewness in the spot market does not increase the explanatory power of the model by a huge margin. The estimated coefficient for skewness is insignificant, indicating that market participants are more concerned with volatility in the spot market than with higher moments of the return distribution. However, the coefficient for returns in the spot market r_t is positive, suggesting that an increase in spot prices will increase convenience yields. Given that convenience yields throughout the sample period were typically negative, this suggests that overall the deviation from the cost-of carry relationship is reduced with increasing spot prices.

Let us now consider the results for *Models III-VI*, including additional dummy variables for specific futures contracts. For *Model III* and *Model IV*, we find a highly significant coefficient $\hat{\gamma} = -0.0135$ for the Phase III dummy variable. As expected, the model confirms that convenience yields for Phase III futures contracts are significantly more negative (of greater magnitude in absolute terms), what is also indicated in Table 2. Including $d_{phaseIII}$ into the model also increases the explanatory power from $R^2 = 0.721$ to $R^2 = 0.804$ (*Model I* in comparison to *Model III*), and from $R^2 = 0.722$ to $R^2 = 0.805$ (*Model II* in comparison to *Model IV*), respectively. However, these results also point towards heterogeneity across individual contracts, questioning the consistence of the OLS estimates in the most simple model specifications (5) and (7). We find that while the signs and significance of the estimated coefficients remain unaffected, the estimates of the coefficients are changed. While the effects are rather small for $\hat{\beta}_1$ (coefficient for the interest rate), the coefficients $\hat{\beta}_2$ (banking) and $\hat{\beta}_3$ (variance in the spot market) show more considerable changes, for example from $\hat{\beta}_2 = -0.0183$ (*Model I*)to $\hat{\beta}_2 = -0.0098$ (*Model III*) and from $\hat{\beta}_3 = -4.0921$ (*Model I*) to $\hat{\beta}_3 = -3.8353$ (*Model III*), respectively. At the same time the standard error of the estimates for these variables is reduced, since some of the heterogeneity is picked up by the introduced Phase III dummy variable. However, all signs as well as the significance of the coefficients remain unchanged, emphasizing the importance of the variables as driving factors of the observed convenience yields.

Further investigating the issue of heterogeneity, we consider results for *Model V* and *Model VI* that include dummy variables for the individual contracts in the pooled OLS estimation. Note that as pointed out before, this specification can be considered as a convenient way to carry out fixed effect analysis (Wooldridge, 2010), what seems to be more appropriate given the heterogeneity across individual contracts. We find that none of the dummy variables for Phase II futures contracts is significant, while all dummies for Phase III contracts are negative and significant at the 1% level. Estimates for $\hat{\gamma}_5 - \hat{\gamma}_7$, i.e., 2013, 2014 and 2015 futures contracts for *Model V* range from $\hat{\gamma}_5 = -0.0120$ to $\hat{\gamma}_7 = -0.0162$, with similar results for the extended *Model VI*. Using individual dummies for the contracts further increases the explanatory power of the model to $R^2 = 0.812$ (*Model V*) and $R^2 = 0.813$ (*Model VI*). Again, estimated coefficients for the interest rate $\hat{\beta}_1$ only exhibit minor changes, while the coefficients $\hat{\beta}_2$ (banking) and $\hat{\beta}_3$ (variance in the spot market) again exhibit more considerable changes. For example, *Model V* yields $\hat{\beta}_2 = -0.0080$ and $\hat{\beta}_3 = -3.6747$ in comparison, while the standard error of the estimates is further reduced as a result of introducing the contract specific dummy variables. So our results point towards inconsistent estimates of a standard pooled OLS model, and suggest the use of a fixed effect or dummy variable estimator.

At the same time, the results for *Model V* and *Model VI* illustrate that a large variation in the dynamics of the observed convenience yields is actually explained by the suggested explanatory variables. All variables remain significant and show the expected sign, in line with the formulated *Hypothesis 1-3*.

Overall, our results provide strong evidence for the impact of the suggested variables as key drivers of observed convenience yields dynamics during Phase II. With regards to *Hypothesis 1*, we find that lower risk-free interest rates decrease observed convenience yields in the EU-ETS. For all model specifications *I-VI*, the estimated coefficients are positive and significant at the 1% level, suggesting that the drop in short-term interest rates has contributed to the change from initial backwardation to contango for the market and the decline in convenience yields.

We also find strong evidence for the impact of the increased number of surplus allowances on the convenience yields as stated in *Hypothesis 2*. Our models yield a negative coefficient for the banking variable, suggesting that the rising number of surplus allowances has led to a further decrease in observed convenience yields during Phase II. While the absolute magnitude of the coefficients becomes smaller, when additional dummy variables for the trading periods or individual contracts are included into the model, for all model specifications the coefficients remain highly significant at the 1% level. Thus, our results confirm the negative relationship between the convenience yield and inventories as it has been suggested for other commodity markets (Pindyck, 2001).

Considering the relationship between volatility in the EUA spot market and the convenience

Model	I	II	III	IV	V	VI
Intercept	-0.0192***	-0.0192***	-0.0180***	-0.0180***	-0.0190***	-0.0191***
	(0.0019)	(0.0019)	(0.0015)	(0.0015)	(0.0032)	(0.0032)
INT_t	0.0061***	0.0062***	0.0059***	0.0059***	0.0059***	0.0060***
	(0.0006)	(0.0006)	(0.0006)	(0.0006)	(0.0005)	(0.0005)
$BANK_t$	-0.0183***	-0.0184***	-0.0098***	-0.0099***	-0.0080***	-0.0081***
	(0.0032)	(0.0032)	(0.0026)	(0.0026)	(0.0024)	(0.0023)
VAR_t	-4.0921***	-4.1411***	-3.8353***	-3.8941***	-3.6747***	-3.7350***
	(0.9349)	(0.9358)	(0.6719)	(0.6657)	(0.6761)	(0.6696)
r_t		0.0146***		0.0133***		0.0127***
		(0.0044)		(0.0039)		(0.0039)
$SKEW_t$		0.0005		0.0009		0.0010
		(0.0007)		(0.0007)		(0.0007)
Phase III			-0.0135***	-0.0135***		
			(0.0023)	(0.0023)		
2010					0.0029	0.0029
					(0.0034)	(0.0034)
2011					0.0009	0.0009
					(0.0032)	(0.0031)
2012					-0.0012	-0.0012
					(0.0033)	(0.0032)
2013					-0.0120***	-0.0121***
					(0.0039)	(0.0038)
2014					-0.0160***	-0.0161***
					(0.0040)	(0.0039)
2015					-0.0162***	-0.0163***
					(0.0041)	(0.0041)
F-stat	4030	2020	4790	3220	2240	1850
p-value	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001
adj R^2	0.721	0.722	0.804	0.805	0.812	0.813
Obs	4685	4685	4685	4685	4685	4685

Table 4: Estimation results for the specified Models I-VI for convenience yields of 2009-2015 futures contracts. We report estimated coefficients as well as Newey-West HAC standard errors in parentheses. The asterisks indicate significance of the variable at the 1% (***), 5% (**) and 10% (*) level of significance.

yield, we find unambiguous support for *Hypothesis 3*. There is a significant negative relationship between spot market volatility and observed convenience yields such that increased variance in the spot market further decreases the convenience yield. These findings suggest that higher volatility and rising uncertainty about EUA price behavior significantly increases the demand for hedging and leads to an increase in observed futures prices. As a result, EUA futures prices exhibit strong contango, in particular during periods of higher volatility in the spot market. Similar results have also been obtained for electricity markets, where, for example, Botterud et al. (2010), Handika and Trück (2013), Redl et al. (2009) and Weron and Zator (2014) find a significant relationship between risk premiums or convenience yields and spot price variance.

With regards to including additional explanatory variables into the model, we find that returns and skewness in the EUA spot market do not provide a significant increase in the explanatory power of the models. The estimated coefficient for skewness is not significant in any of the models. However, the estimated coefficient for spot returns is significant and positive, suggesting that a price increase in the spot market will typically reduce the magnitude of the (negative) convenience yield. Thus, rising spot prices have a tendency to reduce the deviation from the cost-of-carry relationship and, therefore, consumers' willingness to pay an additional risk premium in the futures market.

5. Conclusions and Policy Implications

We provide an empirical study on convenience yields in CO_2 allowance futures prices during the first Kyoto commitment period from 2008 to 2012. In particular, we examine deviations from the cost-of-carry relationship for Phase II and Phase III futures contracts and the driving factors for the dynamics of observed convenience yields for emission allowances. While the connection between spot and futures markets has been thoroughly investigated for other commodities such as oil, electricity, gas or agricultural products, so far only a small number of studies have analyzed the convenience yield and risk premiums in the EU-ETS.

Our findings suggest that during the considered sample period,i.e. the first Kyoto commitment period, the EUA market has changed from an initial short period of backwardation to contango with significant negative convenience yields. Observed average yields range from -1% to -2% for contracts with delivery in 2009-2012, while they range from -3.5% to -5% for Phase III futures contracts with delivery in 2013, 2014 and 2015. Overall, our results indicate a significant deviation from the cost-of-carry relationship for EUA contracts and suggest that unlike many other commodities, carbon futures do not exhibit backwardation. To the contrary, we find that futures contracts are priced at a significantly higher level than implied by the cost-of-carry relationship. This suggests that consumers in EUA markets are interested in buying insurance against rising prices and are willing to pay an additional risk premium for a hedge against increased prices or shortage of EUAs in future periods, such as Phase III.

We then analyze the driving factors of the observed negative convenience yields in the EU-ETS by examining the impact of interest rate levels, banking and surplus allowances, as well as factors related to the dynamics of the EUA spot market. Our findings suggest that a high percentage of the variation in convenience yields can be explained by these factors. More specifically, we find that the drop in risk-free rates during the financial crisis and the subsequently low interest rate levels, have had a significant impact on convenience yields. While the yields were initially very small but positive during 2008, with decreasing interest rates they have become predominantly negative since the second half of 2008. While risk-free rates have remained at a very low level ever since, also average convenience yields for Phase II and Phase III futures contracts have typically been negative since 2009. We also find evidence for the negative relationship between the convenience yield and inventory as it has been suggested in the theory of storage. Overall, convenience yields become increasingly negative as the number of surplus allowances rise towards the middle end of the Kyoto commitment period. We also find that the variance in the EUA spot market has a significant impact on observed convenience yields. The relationship is negative, implying that increased price volatility in spot prices further decreases convenience yields. This behavior also confirms that market participants are willing to pay an additional risk premium in the futures market for a hedge against increased uncertainty about EUA prices.

Our results provide important insights on the relationship between EUA spot and futures contracts and the drivers of convenience yields in this relatively new and unique market. Thus, our work contributes to the literature on the determinants and empirical properties of convenience yields (Casassus and Collin-Dufresne, 2005; Bollinger and Kind, 2010; Prokopczuk and Wu, 2013). We also believe that our results could be useful for the development of trading strategies in commodity futures markets, a topic that has gained increased interest in the literature in recent years (Gorton and Rouwenhorst, 2006; Miffre and Rallis, 2007; Chng, 2009; Rouwenhorst and Tang, 2012). Based on the findings of this study, a thorough investigation of the relationship between convenience yields in the EU-ETS and the proposed factors during Phase III should be conducted in future work.

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