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The inconvenience yield of carbon futures

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ABSTRACT

Since 2009, the European Carbon Futures Market has been in a permanent contango situation that is characterised by systematic negative convenience yields that allow investors to exploit profitable arbitrage opportunities. The objective of this paper is to analyse the possible drivers of these negative convenience yields. Our empirical results indicate that although some carbon trading variables are behind this contango situation, the carbon inconvenience yield is better explained if other financial markets and variables are considered, suggesting a financialization of the European Carbon Futures Market.

1. Introduction

Since the European Union Emissions Trading System (from now on, EU ETS) was launched, carbon spot prices have been systematically below the prices of futures contracts. This fact has caused a scenario of long-lasting negative carbon convenience yields which, in turn, has attracted the attention not only of academics but also of carbon traders interested in exploiting arbitrage opportunities between carbon spot and futures markets. The present study aims to extend the existing literature on carbon convenience yields by examining whether some financial market variables, as well as the carbon spot price and its volatility, can also assist in explaining the observed contango situation. This would support our claim that the long positions taken on European Union Allowances (from now on, EUA) carbon futures by portfolio managers and passive investors would lead to higher prices in the futures market as compared to the spot market and, consequently, their trades would provide the explanation for the situation of permanent contango.

Several studies have tried to identify the drivers of the contango situation detected in the carbon spot and futures markets. Borak et al. (2006) observed that the European Energy Exchange (EEX, from now on) changed from initial backwardation (spot price higher than futures price) to contango (spot price lower than futures price) after May 2006. Furthermore, they found a significant positive relationship between the spot price level and convenience yields, and that the spot price volatility exhibits negative correlation with convenience yields. A contangoed carbon market was also observed by Uhrig-Homburg and Wagner (2009) and Daskalakis et al. (2009). They analysed several European Carbon Futures markets (ECX, Nord Pool and EEX) during Phase I (2005–2007) and both noticed that, from May 2006 onwards, the inter-period futures market seemed to be in contango as futures contracts initiated in Phase I and with the maturity in the next phase were quoted substantially higher than spot prices. Furthermore, Daskalakis et al. (2009) suggested that a possible explanation for this situation could be based on the prohibition on banking allowances from Phase I to the following phase and on the fact that the allowance allocations for the period 2008–2012 were not known before the end of 2007.

Chevallier (2009a), Madaleno and Pinho (2011) and Charles et al. (2013) analysed the convenience yield for several European carbon markets (BlueNext, EEX and ECX) for different sample periods that range from 2006 to 2012. The results of all the above-mentioned papers are the same: the three carbon markets appear to be in contango, no matter the sample period or the maturity of the futures contracts. More recently, Trück and Weron (2016) studied the determinants and empirical properties of convenience yields, considering BlueNext spot and ECX futures prices. They analysed the December futures contracts from 2008 to 2012 and their findings suggest that the market changed from an initial short period of backwardation to contango with substantial negative convenience yields. Their results indicate a positive relationship between convenience yields and interest rates, which turns into a negative link with regard to surplus allowances levels and spot market volatility. Finally, Bredin and Parsons (2016) examined the dynamics of the carbon term structure in the EU ETS between 2005 and 2014. They applied the Nelson and Siegel (1987) model to obtain the term structure of both interest rates and carbon convenience yields. In contrast to Trück and Weron (2016), they observed that the implied convenience yield is too large and varies too dramatically to be explained by market interest rates, regardless of which rate one

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employs. Furthermore, they found that EUA futures prices often embodied an implied convenience yield in the neighbourhood of −4% to −6% and suggested that this negative convenience yield may reflect the lack of arbitrage due to financial constraints.

In summary, negative convenience yields have been observed in all the European Carbon Futures markets since 2006. Furthermore, all the studies that have analysed drivers affecting convenience yields have obtained similar results regarding the carbon spot price and volatility, which are positively and negatively correlated, respectively, with the convenience yield.

The carbon contango situation detected in the above-mentioned carbon literature is comparable to that observed by Bouchouev (2012) for the oil market. Specifically, he observed that, since 2009, financial investors were buying oil futures as protection for their larger investments in other asset classes and as a hedge against inflation. The entry of new financial participants has also been observed by Irwin and Sanders (2012) in the commodity futures arena. Following these authors, investments that track a commodity index have become an accepted alternative investment for institutions and pension funds. These new types of positions generally follow an indexing approach based on passive investments that are long-only.

Some authors have analysed the advantages of including carbon assets in financial portfolios. Chevallier (2009b) illustrated the benefits of using carbon assets for diversification purposes in portfolio management. Mansanet-Bataller and Pardo (2011) and Afonin et al. (2018) highlighted these benefits, in a portfolio context, during the pilot stage of the EU ETS in Phase I once the short-selling option was added. Recently, Zhang et al. (2017) examined the time-varying correlations between carbon allowance prices and other financial indices during Phase III of the EU ETS. Their results showed that the relationship of the carbon price with other financial indices has weakened over time and given the relative independence of carbon assets from other financial assets, the authors argue for the diversification benefits of including EUAs in traditional financial portfolios. Furthermore, they tested the performance of a portfolio with/without carbon assets from 2013 to 2016 and concluded that including EUAs may not generate a higher portfolio return rate, but it does help to reduce the volatility of an optimised portfolio, no matter which optimisation strategy is utilised. Finally, Pardo (2021) has shown that EUAs can provide a hedge against unanticipated inflation rates. He observed a positive and marked relationship between EUA nominal returns and unanticipated changes in purchasing power, which suggests that portfolio managers can use EUAs to shield their portfolios from the ravages of unexpected inflation.

Based on the above results, we hypothesise that financial investors buy EUA futures as a strategy to exploit both the high profitability of EUAs (the EUA price has increased by more than 50% from 2009 to 2020) and the low cross-correlation between the returns of carbon permits and other financial assets. If the demand from futures buyers exceeds the supply, futures prices will begin to trade at a relative premium, creating a contango situation. The carbon warehousers will collect that premium (i.e. the negative convenience yield) by selling relatively expensive futures to the portfolio managers and/or financial hedgers until the negative convenience yield offsets the storage costs.

The contribution of this paper to the carbon literature is twofold. Firstly, we analyse the influence of carbon market variables on the negative convenience yield but, unlike previous papers, we also analyse the relationship between the negative convenience yield and other financial assets that exhibit low correlation with the price of the emission rights, such as benchmarks from equity markets, fixed income markets and sovereign bonds. Secondly, we study the comovement between the negative convenience yield and the conditioning variables using a quantile regression (QR) approach that provides specific insights into the impacts of the carbon and non-carbon-related variables on the convenience yield under different market scenarios, such as bearish and bullish markets. This paper is organised as follows. Section 2 details the main features of the EU ETS. Section 3 explains the methodology. Section 4 presents the data and the empirical results. Section 5 concludes.

2. European Union Emissions Trading System

The EU ETS was established in 2005 as a market-based mechanism to reduce carbon dioxide and it covers around 45% of the emissions of the EU. The EU ETS is organised into phases or trading periods. Phase I (2005–2007), widely considered as a pilot phase, involved installations belonging to the power sector and the manufacturing industry. Phase II went from 2008 to 2012 and coincided with the first commitment period of the Kyoto Protocol. At the end of this period, the carbon emissions from the aviation sector were included in the EU emissions restrictions. During Phases I and II the cap was established, taking as reference the aggregation of the national allocation emission plans of each member state, and around 90% of allowances were allocated for free. Phase III (2013−2020) introduced two main changes with respect to the earlier periods. Firstly, a single EU-wide cap for stationary sources was fixed, instead of the previous system of national allocation plans. This single cap is reduced annually by a linear reduction factor, currently 1.74%, which will be increased to 2.2% for Phase IV (2021−2030). Secondly, starting in Phase III, auctioning is the default method for allocating allowances, instead of free allocation. The general principle is that all allowances not allocated free of charge are to be auctioned. The annual volumes of general allowances to be auctioned and the timing and frequency of auctions are regulated by the European Commission, which has estimated that 57% of the total amount of allowances will have been auctioned in 2013–2020.[1]

Furthermore, on 1 January 2019, the Market Stability Reserve (MSR) began to operate, taking from the market or reinjecting into it a predefined number of allowances for two purposes: to address the supply–demand imbalance of allowances in the EU ETS and to improve its resilience against future shocks. Each year, the European Commission publishes by 15 May the total number of allowances in circulation. This serves as the exclusive indicator as to whether allowances will be placed in or released from the reserve.[2]

Among the peculiarities of the EU ETS, it is interesting to highlight that participants have the possibility of using allowances from the present period in the following one, known as banking, or just the opposite, where participants can *'borrow'* allowances from future periods to meet current emissions requirements. Borrowing is allowed only in the same phase and banking is allowed in both the same phase and between phases.

The main asset of the EU ETS is the EUA, which grants the owner the right to emit one tonne of CO_2 or equivalent gas. EUAs can be traded in spot, futures and options markets, where the futures market is by far the leader, followed by the spot market. There are two main platforms that handle carbon futures contracts, the EEX and the Intercontinental Exchange (ICE ECX). The ICE ECX is the most active platform and most of the volume is concentrated there, with the price of the ICE EUA December futures contract being considered as the benchmark for the European carbon price.

The ICE ECX Futures Europe market operates an electronic order-driven market with market makers and brokers where trades submitted are listed in a unique Limited Order Book and are executed following

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[1] See https://ec.europa.eu/info/energy-climate-change-environment_en for further information on the European Union policy on Energy, Climate Change and Environment (last accessed in April 2021).

[2] See both https://ec.europa.eu/clima/policies/ets_en and https://icapcarbonaction.com/en/ets-map for detailed descriptions of the functioning of the EU ETS (last accessed in April 2021).

a price and time criteria. The daily session starts with a pre-open period of 15 min (from 6:45 a.m. UK local time) to enable market members to input orders in readiness for the beginning of trading. The pre-trading period finishes with a single call auction, where the opening price and the allocated volume are determined by an algorithm. During the continuous session, from 7:00 to 17:00, investors can submit limit orders, market orders and block orders. The futures market price settlement period runs from 16:50:00 to 16:59:59 UK local time and is the weighted average price during this period. The futures contracts are traded in lots. Each lot equals 1000 t of CO_2 equivalent, that is, 1000 EUAs. The minimum tick size was €0.05 until 27 March 2007 when it changed to €0.01. The settlement period for the ICE Futures Contract ceases trading at 17:00 UK local time on the last Monday of the contract month and the contracts are settled and delivered by the transfer of the EUAs from the seller's account to the buyer's account at the Union Registry.

3. Methodology

3.1. Carbon convenience yield

The theory of storage explains the difference between futures and spot commodity prices, focusing on the costs and benefits of holding physical stocks of the commodity. According to this theory, the cost of carry is defined in terms of the risk-free interest forgone by investing in one unit of commodity at the spot price, the per-unit physical storage cost, and the convenience yield.

Specifically, we define the carbon convenience yield as the flow of benefits associated with holding the allowance to emit one tonne of carbon dioxide in the present rather than in the future. This convenience yield can be obtained from the cost-of-carry relationship stated by Working (1949) and Brennan (1958) represented in the following no arbitrage condition:

$$P_{Fut,t} = P_{Spot,t}e^{\left(r_{t,T}+sc_{t,T}-cy_{t,T}\right)\frac{(T-t)}{365}} \tag{1}$$

where $P_{Fut,\ t}$ is the futures price at t with delivery at T; $P_{Spot,\ t}$ identifies the EUA spot price at time t; $r_{t,\ T}$ is the continuously compounded per period risk-free interest rate from t to T; and $sc_{t,\ T}$ and $cy_{t,\ T}$ are the cost of storage and the convenience yield, respectively, over the period t to T. All the variables that appear in Eq. (1) are observable except for the convenience yield, which must be estimated. Solving Eq. (1) for the convenience yield, we obtain:

$$cy_{t,T} = r_{t,T} + sc_{t,T} - \frac{365 \times log\left(\frac{P_{Fut,t}}{P_{Spot,t}}\right)}{T-t} \tag{2}$$

Therefore, following Eq. (2), the convenience yield can be broken down into three terms, the first of which is the risk-free interest rate. In our case, we have used the EURIBOR index. As the EURIBOR forward curve is published at fixed tenors, we have obtained the value of the interest rate from t to maturity on T ($r_{t,\ T}$) by linear interpolation using the following relationship:

$$\frac{r_{t,m}-r_{t,n}}{t_m-t_n} = \frac{r_{t,T}-r_{t,n}}{T-t_n} \tag{3}$$

where $t_m > T > t_n$.

The second term makes reference to the storage costs. These costs must be paid to a National Registries of Emissions Allowances of each of the member states of the European Union and all the registries are integrated within a common platform, the Union Registry, which is managed by the European Commission. The fees applied for an account opening and its maintenance are normally charged at the moment in which the account is opened, and the billing period is usually annual. The amount of the fees is around €1700 per year; however, this amount is negligible in relative terms for financial investors who want to exploit carbon arbitrage opportunities and for this reason these fees are not considered in our study.[3]

The third component of the convenience yield is the slope of the futures term structure. We compute the slope as the logarithm of the ratio between the nearest to delivery EUA futures price and the EUA Daily futures, which acts as spot in the European Carbon Market:

$$slope_{t,T} = \frac{365 \times log\left(\frac{P_{Fut,t}}{P_{Spot,t}}\right)}{T-t} \tag{4}$$

A market is in a contango situation when the forward price of a futures contract is higher than the spot price. However, when the slope is higher than the sum of the risk-free interest rate plus the storage costs, the convenience yield becomes negative and it is said that the market is in a normal contango situation.

Following Tilton et al. (2011), a contango that exceeds the cost of storage and interest will induce some traders to buy spot and sell futures, to earn from the arbitrage. The inter-temporal arbitrage will raise the spot price and reduce the futures price, simultaneously. In this way, the work of arbitrageurs tends to stabilise the strong contango at a level where the gains from arbitrage settle at or near zero. However, both the situation of permanent normal contango that is observed in the European Carbon Market and the absence of costs of storing permits make it necessary to identify the sources of the carbon inconvenience yield (see Salant, 2015).

3.2. Determinants of the convenience yield

We follow the idea proposed by Prokopczuk and Wu (2013) that the convenience yields of commodities are exposed to both commodity-specific and systematic factors. Specifically, we have identified two groups of key factors that might explain the behaviour of the convenience yield. The first group of variables are measures directly related to the European Carbon Market and the second group refers to the main international benchmarks for equity and fixed income markets.

3.2.1. Carbon-related variables

Based on the previous empirical evidence, we have found the spot price level as a determinant of the convenience yield. Following Borak et al. (2006), facing an increase in spot prices, market participants may go long in the futures market to hedge against further increasing prices in forthcoming periods. Therefore, we should expect a positive relationship between the EUA spot price and the convenience yield.

A second factor that can affect the convenience yield is the variability of the commodity price. Following Pindyck (2001), the volatility of the underlying asset should affect the marginal value of storage (convenience yield), production and price. Several papers consider the convenience yield as a real option written on inventory and that its value should rise with an increasing volatility of the underlying asset (see Prokopczuk and Wu, 2013). However, another line of research points out that an increase in the variance in the spot market would increase the demand for buying futures contracts and, therefore, increase futures prices. In this case, we would expect a negative relationship between carbon market volatility and observed convenience yields (see Trück and Weron, 2016).

Additionally, we have studied if the behaviour of carbon traders affects the convenience yield. Specifically, we have analysed hedging

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[3] Both legal entities and individuals can open an account in a National Registries of Emissions Allowances to trade with EUAs. There are different types of accounts depending on whether the institution is subject to the Kyoto Protocol, whether the objective is for trading or holding purposes, or whether the entity is an aircraft operator. All these accounts have the same requirements regarding fees to pay. See both https://www.gov.uk/guidance/eu-ets-charges and https://www.renade.es/ing/Home.aspx for further information on the costs involved in opening and maintaining an account. (Last accessed in April 2021).

and speculative pressure. Regarding hedging pressure, regulated installations can take short positions in the carbon futures market to hedge their spot positions. This supply of futures contracts would generate a downward bias in the futures price and an increase in the carbon convenience yield. However, Hirshleifer (1990) suggests that hedgers face quantity risk as well as price risk and they might take long instead of short futures positions. In this case, the hedging pressure would provoke an upward movement in carbon futures prices and a decrease in the convenience yield. Regarding speculative pressure, Lucia et al. (2015) indicate that a high degree of speculation in the carbon futures markets could move futures prices well above or below the levels justified by supply and demand fundamentals. Therefore, a high speculative pressure can decrease or increase the carbon convenience yield.

Finally, it seems that the inventory of emission rights should play an important role in the sign and magnitude of the carbon convenience yield. Expectations of a shortfall in emission rights should increase the demand for EUAs and increase the convenience yield. However, the unlimited banking that has been allowed since 2008 and the long-lasting expectations of an excess of emission rights that has characterised the EU ETS throughout its history may have caused the opposite situation. Unfortunately, EUA inventory levels are published annually, which prevents a proper analysis with more frequent data.

3.2.2. *Financial variables*

For the second group of variables, we have selected some European benchmarks and broad-based indexes that are usually followed by financial investors that try to match the chosen benchmark. Furthermore, we have also considered the analogous benchmarks for the North American region due to the importance of these indices for global portfolio managers. The underlying idea is that the low cross-correlation between carbon assets and these broad-based indices or benchmarks make the carbon market an appealing way to hedge the positions taken on European or North American financial instruments by passive investors.

Based on the previous empirical evidence related to the benefits of portfolio diversification through the inclusion of carbon assets, we have considered eight benchmarks that will be briefly described later in the section devoted to data. These eight benchmarks are: the MSCI Europe Index and MSCI North America Index, as references for equity markets; the Euro STOXX 50 volatility index (VSTOXX) and S&P 500 volatility index (VIX), as proxies for European and American stock market volatility; the IBOXX EURO Corporates AAA Index and IBOXX USD Corporates AAA Index, as references for the fixed income markets; and the 10-year zero-coupon sovereign bond yield in Germany and the USA, as benchmarks of investments in sovereign bonds. If financial investors bought carbon futures as a protection for their larger investments in asset classes referenced to the above-mentioned benchmarks, we should obtain a negative relationship between these financial variables and the carbon convenience yield that would be more pronounced in bearish markets.

3.3. *Quantile regression*

To study the effect of both carbon-related variables and other financial variables on the carbon convenience yield, we have performed a multivariate regression analysis by applying the Quantile Regression (QR) methodology proposed by Koenker and Bassett (1978). In the case of normality, the Ordinary Least Squares (OLS) estimator is more efficient, but when the distributions are non-normal, the precision of the QR estimator improves upon OLS. Additionally, the QR approach aims to provide an estimation of the quantile conditional distribution of the dependent variable and not an expected conditional distribution as in OLS. Therefore, in our context, QR provides a method for modelling the rates of change in the carbon convenience yield at multiple points of the distribution when such rates of change are different (see Davino et al., 2013, pp.110–118).

The QR model of Koenker and Bassett (1978) can be expressed as:

$$y_t = x_t\beta_\theta + u_{\theta,t} \text{ with } Q_\theta(y_t|x_t) = x_t\beta_\theta \tag{5}$$

where $Q_\theta(y_t|x_t)$ is the θth conditional quantile of y given x ($0 < \theta < 1$). The estimation of β_θ is based on the minimisation of the sum of asymmetrically weighted absolute error terms, where positive and negative residuals are weighted differently depending on the quantile chosen:

$$\beta_\theta = argmin_\beta\left\{\sum_{t:y_t>x_t\beta}\theta|y_t - x_t\beta| + \sum_{t:y_t<x_t\beta}(1-\theta)\,|y_t - x_t\beta|\right\} \tag{6}$$

4. Empirical results

4.1. *Data*

In this study, we have employed daily data from 13 March 2009 to 7 April 2020.

Regarding carbon prices, we have used data from ICE ECX Futures Europe, which is the benchmark futures market for carbon emissions trading in Europe. The dataset is composed of ICE EUA futures settlement prices, the highest and the lowest EUA traded prices on each day, the trading volume and the open interest. To carry out this study, we have chosen the ICE ECX EUA December futures contracts with maturities from 2009 to 2020. The reason for this choice is that most of the trading volume by far is concentrated in the December maturities.

Following Carchano et al. (2014), we have used the last day criterion to obtain a front contract series for the futures prices, that is, we switch December futures contracts when the nearest to maturity December contract expires.[4] Furthermore, we have used the ICE ECX EUA Daily Futures settlement prices as a reference for the spot price. The unit of trading of the ICE ECX EUA December Futures Contract and ICE EUA Daily Futures is one lot of 1000 CO_2 EUAs. However, the expiry day of the former contract is the last Monday of the contract month (December) while the latter one is a daily contract.

For the European risk-free rates, we have applied the Reuters zero rates that are estimated from the most liquid interest rate instruments that are available: a combination of deposits, liquid futures contracts and interest rate swaps. Specifically, we have chosen the quotes for maturities for one and seven days, and from one to 12 months. As we have explained in Section 3.1, we have used linear interpolation between the quotes with the next longer and shorter maturity to estimate the risk-free rate for different time horizons until the maturity of the nearby December futures contract.

The intraday volatility (σ_t) has been calculated following the measure proposed by Parkinson (1980):

$$\sigma_t = \sqrt{\frac{1}{4log2}\left(logP_{H,t} - logP_{L,t}\right)^2} \tag{7}$$

where $P_{H,\,t}$ and $P_{L,\,t}$ are the highest and lowest futures prices of each day t. The main advantage of the Parkinson estimator with regard to the close-to-close standard deviation is that it considers intraday information. Consequently, even if two consecutive closing prices were the

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[4] Unlike other energy commodities such as crude oil where traders take the average of the futures prices from one month until five days before the expiry date as the reference price for bilateral operations, in the case of carbon, the settlement price of the last trading day is used not only to liquidate futures positions, but also OTC carbon trades. This is because in the carbon market there is no physical commodity to be delivered on the expiration date. The carbon futures contracts are settled on that date by the transfer of the EUAs from the seller's account to the buyer's account at the Union Registry. Therefore, the last day criterion would be the most appropriate rollover approach to follow from an investor's point of view for any carbon-related asset.

same, these extreme value volatility measures could detect high intraday volatility. Although spot and futures carbon volatility are highly correlated, we have decided to use the latter. The reason is that futures volatility is of great relevance for futures traders because all of them are subject to intraday margin requirements to keep their positions open.

Regarding trader behaviour, we have applied the measure proposed by Lucia and Pardo (2010) as a proxy to study both hedging and speculative behaviour in the European Carbon Market. This measure is defined as the ratio between the change in the open interest and the daily trading volume over a day t. The ratio has no dimension and can take any value ranging from −1 to +1. A positive (negative) number indicates that the number of open (closed) positions is greater than the number of closed (open) positions. After calculating the ratio for all the trading days, we have constructed two dummy variables: RH_t and RS_t, which take value 1 when the ratio is in the intervals [0.95, 1] and [−0.01, 0.01], respectively. The first dummy variable is a proxy for hedging pressure, indicating days on which the opening of new positions outnumbers by far the closing of positions, while the second variable is used as a proxy for speculative pressure, identifying days with an abnormal number of intraday traders who open and close carbon futures positions on the same day.[5]

As a benchmark for equity markets, we have selected two MSCI indexes that show the performance of large and mid-cap equities that cover approximately 85% of free float-adjusted market capitalisation of each area. The first is the MSCI Europe Index, which is denominated in euros and includes 435 constituents from 15 European countries; this index was first published on 31 December 1998 with a value of 100. The second is the MSCI North America Index, denominated in US dollars with 701 constituents from the USA and Canada, which began with a value of 100 on 31 December 1969.[6]

Furthermore, we have selected two volatility indexes. Firstly, we have chosen the Euro STOXX 50 volatility index (VSTOXX) as a proxy for European stock market volatility. This index, developed by Goldman Sachs and Deutsche Börse, is calculated daily as the square root of the implied variance of Out-of-The-Money (OTM) puts and calls for the following 30 calendar days. Secondly, we have employed the volatility index published daily by the Chicago Board of Option Exchange (CBOE), commonly known as VIX. The VIX Index is intended to provide an instantaneous measure of how much the market expects the S&P 500 Index to fluctuate in the 30 days from the time of each tick of the VIX Index. The components of the VIX Index are at- and out-of-the-money put and call options with more than 23 days and less than 37 days to a Friday S&P 500 index expiration date. The index was introduced by Whaley (1993) and adopted by CBOE, which started to compute it in 1993.[7]

Regarding fixed income markets, we have chosen both the IBOXX EURO Corporates AAA Index and the IBOXX USD Corporates AAA Index. These are calculated daily by IHS Markets and represent the AAA investment-grade fixed income markets for denominated bonds in Euro and USD, respectively.[8]

Finally, the 10-year zero-coupon sovereign bond yields in Germany and USA are considered as the guaranteed return of an investment in sovereign bonds. The Germany 10-year zero-coupon yield is calculated using a set of coupon bonds, bills, swaps or a combination of these instruments using a standard bootstrapping method with at least four instruments with different tenors. Regarding the US Treasury zero-coupon yield curve at 10 years, it is expressed in zero-coupon returns and provides a daily estimated yield curve with maturity in 10 years. For the most part, the yield curve is computed using bid-side market quotations for the on-the-run securities obtained by the Federal Reserve Bank of New York. Since 1980, the Svensson (1994) model has been employed to fit the yield curve.[9]

4.2. Summary statistics

To estimate the convenience yield, we have previously calculated the slope of the futures term structure ($slope_{t,\,T}$) and the continuously compounded per period risk-free interest rate ($r_{t,\,T}$) from t to T by applying Eqs. (3) and (4), respectively. Fig. 1 depicts the evolution of the convenience yield, the slope and the interest rate for the analysed period. The evolution of the negative convenience yield confirms that the carbon market has been in a permanent normal contango situation since 2009 regardless of whether the European economy has been in recession (lower emissions) or expansion (higher emissions). It can be observed that the slope is always higher than the estimated risk-free interest rate except at two specific moments, December 2009 and December 2016.[10]

The contango situation detected in the carbon market is long-lasting, a fact which implies that arbitrage opportunities will remain while the negative convenience yield offsets the storage costs. However, the scarce supply of EUAs in the spot market, as a result of trading restrictions in the futures market caused by the existence of initial and maintenance margin requirements, could lead to carbon warehousers being unable or unwilling to engage in new cash and carry trades.[11]

Panel A of Table 1 contains summary statistics for the final dataset we have chosen. EUA futures returns and spot returns exhibit similar features with maximum and minimum values around 23% and − 43%, respectively. The mean and the median of the convenience yield is negative, with a maximum of 7.76% and a minimum of −10.77%. In the three cases, there is evidence of negative skewness and large kurtosis values. The significant Jarque–Bera test statistics confirm that convenience yield and return distributions are non-normal.

Panel B of Table 1 presents the tabulation of the CY series classified in five categories in ascending order, displaying the counts, the percentage counts and the cumulative counts. Of note, only 69 out of 2840 observations are higher than zero, indicating that the carbon convenience yield has remained in negative territory for 97.57% of the days of the sample, and most of the values (97.08%) are between minus 5% and zero.

Table 2 shows the summary statistics for the financial market variables. Given that some variables are expressed in US dollars, they have

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[5] See Table 1 in Lucia and Pardo (2010) for a simulated example of the daily trading activity in a fictitious futures market in order to clarify the use of these ratios as proxies for measuring the relative importance of hedging/speculative demand in empirical analyses.

[6] Further information about the MSCI indexes can be found at https://www.msci.com/documents/10199/f6179af3-b1d1-4df0-8ac9-215451f3ac0a for MSCI Europe and https://www.msci.com/documents/10199/7ded14f4-a8c8-49f5-af2e-11b2fe1f3cfe for MSCI North America.

[7] For additional information about VSTOXX and VIX see https://www.stoxx.com/index-details?symbol=V2TX and http://www.cboe.com/vix/, respectively.

[8] See https://ihsmarkit.com/index.html for further information about these indices.

[9] A detailed description and historical data of the Germany and the US Treasury 10-year zero-coupon yield can be obtained from https://www.bundesbank.de/en/statistics/time-series-databases and https://www.federalreserve.gov/data/nominal-yield-curve.htm, respectively.

[10] It is worth noting that the slope exhibits some peaks/valleys on days preceding the maturity of the EUA December futures contract. These values are due to occasional and small differences in absolute terms between the futures and the spot prices that increase sharply when they are entered into Eq. (4) to annualise the slope. Although these differences are corrected on the following day, they caused five values of the convenience yield to reach values higher than 12% in absolute terms. These have been omitted from the final analysis as they are considered to be atypical.

[11] Parties to a futures contract are required to make an initial margin payment on the contract. The initial margin requirement represents the amount required by the exchange when a futures position is opened, while the maintenance margin requirement is the minimum amount required by the exchange that must be maintained at any given time to keep the futures position open. Although ICE Clear Europe charges an initial and variation margin that represents 15% of the nominal position, it is possible that the broker may require additional funds to maintain the position if carbon volatility increases.

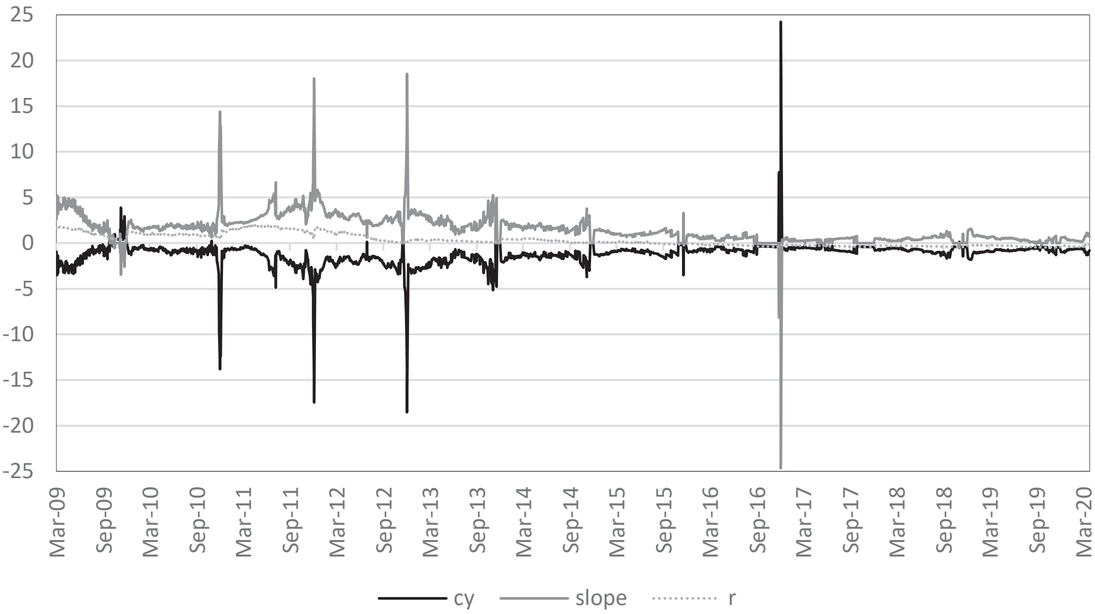

Fig. 1. Convenience yield, slope and interest rate.

This figure depicts the convenience yield ($cy_{t,\ T}$),the slope of the futures term structure ($slope_{t,\ T}$) and the continuously compounded per period risk-free interest rate ($r_{t,\ T}$) from t to T by applying Eqs. (2), (3) and (4), respectively. They are expressed in percentage and in annual terms. The sample period consists of data from 13 March 2009 to 7 April 2020.

Table 1

Descriptive statistics of the carbon data series.

Panel A: Descriptive statistics

	$R_{Spot,\ t}$	$R_{Fut,\ t}$	CY_t
Mean	0.0185	0.0120	−1.1921
Median	0.0000	0.0000	−0.9308
Maximum	23.9870	23.8234	7.7661
Minimum	−43.1441	−43.2077	−10.7751
Std. Dev.	3.1608	3.1509	0.9733
Skewness	−0.9057	−0.9453	−2.0141
Kurtosis	19.8279	19.9690	23.2102
Jarque-Bera	33,945.36***	34,399.33***	50,253.59***
Observations	2844	2832	2840

Panel B: Tabulation of the CY_t series

Value	Count	Percent	Cumulative count	Cumulative percent
[−15, −10]	2	0.07	2	0.07
[−10, −5]	12	0.42	14	0.49
[−5, 0]	2757	97.08	2771	97.57
[0, 5]	67	2.36	2838	99.93
[5, 10]	2	0.07	2840	100.00
Total	2840	100.00	2840	100.00

These panels show the main descriptive statistics of the carbon data series. $R_{Spot,\ t}$ is the logarithmic return of the EUA Daily Futures, $R_{Fut,\ t}$ represents the logarithmic return of the EUA Futures nearby maturity contract and CY_t is the carbon convenience yield. The sample period consists of data from 13 March 2009 to 7 April 2020. The Jarque-Bera statistic tests for the null hypothesis of normality for the distribution of the series. The *** indicate rejection of the null hypothesis at the 1% level.

been converted into € to homogenise all the series. The MSCI North America Index has the lowest return and the highest volatility of the two equity indices. The return of the IBOXX EURO Corporates AAA Index exhibits the lowest mean and volatility of the two fixed income benchmarks. Regarding VSTOXX and VIX, both volatility references display similar statistics. The last two columns show the Germany and the US 10-year zero-coupon yield. It is worth noting the negative yields observed in the German case, whose origin is the non-standard monetary policy measures of the European Central Bank.

4.3. Cross correlation analysis

Table 3 shows the Pearson's cross-correlation coefficients among the chosen variables. We observe that spot and futures returns are positively and significantly correlated at the 1% level (99.91%) and their cross-correlations with the rest of the variables are quantitatively and qualitatively similar. The carbon returns are negatively correlated with the two corporate indexes (IBOXX EURO Corporates AAA Index and IBOXX USD Corporates AAA Index) and with the two measures of volatility (VSTOXX and VIX) at the 1% level, but positively and significantly correlated with the returns of both the MSCI Europe Index and the MSCI North America Index. Finally, we do not observe any relationship between futures/spot returns and the 10-year zero-coupon sovereign bond yields in Germany and the USA. Therefore, EUAs behave as a strong hedge with regard to corporate and volatility indexes, as a diversifier with respect to equity indexes and as a weak hedge with reference to sovereign yields (see Baur and McDermott, 2010).

All the cross-correlation coefficients between European and US benchmarks are positive and significant at the 1% level. The returns of the IBOXX EURO Corporates AAA Index and the returns of the IBOXX USD Corporates AAA Index are highly correlated (47.64%) and the same occurs between the 10-year zero-coupon sovereign bond yields in Germany and USA (74.85%). The correlation between the references belonging to the equity markets are even higher. The returns of the MSCI Europe and North America Indexes, and the VSTOXX and VIX, exhibit cross-correlations of 63.30% and 90.52%, respectively.[12]

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[12] When multiple hypotheses are tested, the likelihood of incorrectly rejecting the null hypothesis increases. To counteract this problem, we have adjusted the probability values for multiple comparisons using the Bonferroni correction. The Bonferroni correction adjusts the probability values by testing each individual hypothesis at a significance level of α/m where α is the desired overall α level of significance and m is the number of hypotheses. In our case, the trial has tested $m = 45$ hypotheses with a desired α of 0.05, then the Bonferroni correction tests each individual hypothesis at $\alpha/m = 0.05/45 = 0.0011$. The results confirm that all the cross-correlation coefficients between European and US benchmarks are positive and significant at the 0.0011 level. The findings of this analysis are available on request from the authors.

Table 2
Descriptive statistics of the financial market data series.

	$R_{MSCI\_EU,\ t}$	$R_{MSCI\_NA,\ t}$	VSTOXX$_t$	VIX$_t$	$R_{IBOXX\_EU,\ t}$	$R_{IBOXX\_NA,\ t}$	$ZC_{Ger,\ t}$	$ZC_{US,\ t}$
Mean	0.0217	0.0479	22.1173	18.0637	0.0062	0.0093	1.2799	2.5680
Median	0.0605	0.0719	20.6274	15.9400	0.0097	0.0217	0.9495	2.4518
Maximum	8.1799	9.6815	85.6206	82.6900	0.8704	2.6015	3.8490	4.4581
Minimum	−12.3144	−13.5122	10.6783	9.1400	−2.0008	−4.1971	−0.8670	0.6203
Std. Dev.	1.0936	1.1326	8.1144	7.5344	0.2249	0.6217	1.2093	0.7061
Skewness	−0.7850	−0.7301	1.8351	2.5828	−0.5332	−0.1746	0.4789	0.4977
Kurtosis	13.3792	19.8970	9.6431	14.1306	6.7162	5.4450	2.0417	2.7269
Jarque-Bera	13,117.48***	34,241.05***	6758.55***	17,485.43***	1748.16***	657.28***	218.61***	122.84***
Observations	2857	2857	2816	2787	2807	2586	2858	2767

This table shows the main descriptive statistics. $R_{MSCI\_EU,\ t}$ is the logarithmic return of MSCI Europe Index; $R_{MSCI\_NA,\ t}$ denotes the logarithmic return of MSCI North America Index; VSTOXX$_t$ denotes the EURO STOXX50 volatility index; VIX$_t$ is the S&P500 volatility Index; $R_{IBOXX\_EU,\ t}$ represents the logarithmic returns of the IBOXX EURO Corporates AAA Index; $R_{IBOXX\_NA,\ t}$ is the logarithmic returns of the IBOXX USD Corporates AAA Index; $ZC_{Ger,\ t}$ is the Germany 10-year zero-coupon yield curve; and $ZC_{US,\ t}$ represents the US 10-year zero-coupon yield curve. The sample period consists of data from 13 March 2009 to 7 April 2020. The Jarque-Bera statistic tests for the null hypothesis of normality for the distribution of the series. The *** indicate rejection of the null hypothesis at the 1% level.

Table 3
Cross-correlation analysis.

	$R_{Spot,\ t}$	$R_{Fut,\ t}$	$R_{MSCI\_EU,\ t}$	$R_{MSCI\_NA,\ t}$	VSTOXX$_t$	VIX$_t$	$R_{IBOXX\_EU,\ t}$	$R_{IBOXX\_NA,\ t}$	$ZC_{Ger,\ t}$
$R_{Fut,\ t}$	0.9991***								
$R_{MSCI\_EU,\ t}$	0.1846***	0.1867***							
$R_{MSCI\_NA,\ t}$	0.1347***	0.1346***	0.6330***						
VSTOXX$_t$	−0.0701***	−0.0711***	−0.1279***	−0.0842***					
VIX$_t$	−0.0627***	−0.0634***	−0.1263***	−0.1416***	0.9052***				
$R_{IBOXX\_EU,\ t}$	−0.0602***	−0.0612***	−0.2275***	−0.0724***	−0.0373*	−0.0362*			
$R_{IBOXX\_NA,\ t}$	−0.0728***	−0.0748***	−0.1400***	0.1445***	0.0239	0.0319	0.4764***		
$ZC_{Ger,\ t}$	−0.0145	−0.0155	0.0285	0.0181	0.3632***	0.3392***	0.0211	−0.0213	
$ZC_{US,\ t}$	0.0233	0.0236	0.0393**	0.0337*	0.0201	0.1170***	0.0114	−0.0214	0.7485***

The table shows Pearson's cross-correlation analysis. $R_{Fut,\ t}$ represents the logarithmic return of the EUA Futures nearby maturity contract; $R_{Spot,\ t}$ is the logarithmic return of the EUA Daily Futures; $R_{MSCI\_EU,\ t}$ is the logarithmic return of MSCI Europe Index; $R_{MSCI\_NA,\ t}$ denotes the logarithmic return of MSCI North America Index; VSTOXX$_t$ denotes the EURO STOXX50 volatility index; VIX$_t$ is the S&P500 volatility Index; $R_{IBOXX\_EU,\ t}$ represents the logarithmic returns of the IBOXX EURO Corporates AAA Index; $R_{IBOXX\_NA,\ t}$ is the logarithmic returns of the IBOXX USD Corporates AAA Index; $ZC_{Ger,\ t}$ is the Germany 10-year zero-coupon yield curve; and $ZC_{US,\ t}$ represents the US 10-year zero-coupon yield curve. The sample period consists of data from 13 March 2009 to 7 April 2020. The null hypothesis is that the Spearman's cross-correlation coefficient is equal to 0. The ***, ** and * indicate rejection of the null hypothesis at the 1%, 5% and 10% level, respectively.

4.4. Quantile regression

Next, we have performed a multivariate regression analysis to detect the key determinants of the carbon convenience yield. Firstly, as we have seen, the Jarque-Bera tests in Table 1 indicate that all the series are non-normal, suggesting the use of methodologies that do not assume normal distribution in the data distribution. Secondly, the high degree of cross-correlation between European and US benchmarks observed in Table 3 can cause multicollinearity problems in a multivariate regression analysis, such as the reduction of the precision of the estimated coefficients of the independent variables that are statistically significant.

On the one hand, to deal with the non-normality, we have applied the Quantile Regression (QR) methodology. On the other hand, to deal with multicollinearity, we have removed some of the highly correlated independent variables in the quantile regression. Specifically, we have preliminarily decided to eliminate the US variables. Consequently, based on these decisions, the following model has been estimated:

$$cy_t = \alpha + \beta_1 R_{Spot,t} + \beta_2 \sigma_t + \beta_3 RH_t + \beta_4 RS_t + \beta_5 R_{MSCI\_EU,t} + \beta_6 VSTOXX_t + \beta_7 R_{IBOXX\_EU,t} + \beta_8 ZC_{Ger,t} + \epsilon_t \tag{8}$$

where $R_{Spot,\ t}$ is the EUA spot return; σ_t is the carbon volatility; RH_t and RS_t are the dummy variables that measure the hedging pressure and the speculative pressure, respectively; $R_{MSCI\_EU,\ t}$ is the MSCI Europe Index return; $VSTOXX_t$ is the Euro STOXX 50 volatility index; $R_{IBOXX\_EU,\ t}$ is the IBOXX EURO Corporates AAA Index return and $ZC_{Ger,\ t}$ is the Germany 10-year zero-coupon yield.

4.4.1. Comovement structure between the negative convenience yield and carbon-related variables

Table 4 reports the estimates of the quantile regressions for the convenience yield. Our estimates use the Huber sandwich method for computing the covariance matrix. We present numerical results for nine quantiles from 0.1 to 0.9.

It is interesting to note that the unconditional quantiles, given by the constant term of the QR, are negative and significant at the 1% level for all the quantiles, ranging from −0.67% to −0.31%.

Regarding carbon-related variables, the impact of the spot price is positive and significant at the 1% level for the lower quantiles, whereas we observe no significant effects for the intermediate and upper quantiles. The positive relationship between spot price and convenience yield was also observed by Borak et al. (2006) and Madaleno and Pinho (2011). However, the comovement between the negative convenience yield and the carbon spot price increases in the lowest quantiles indicates that the positive dependence is significant only during the bearish carbon market. A possible explanation for this finding may lie in the fact that in periods of economic recession, the companies that need liquidity and have emission rights could use them as a means of financing, selling EUAs in the spot market and buying them in the futures market, thereby increasing the negative convenience yield.

A completely different shape is observed in the effect of carbon volatility. Its relationship with the convenience yield is negative and

Table 4
Quantile regression analysis.

	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
α	−0.6665***	−0.4822***	−0.4378***	−0.4008***	−0.4157***	−0.4566***	−0.4435***	−0.3192***	−0.3053***
	(0.0933)	(0.0661)	(−7.4459)	(0.0562)	(0.0693)	−0.0420	(0.0402)	(0.0344)	(0.0413)
$R_{Spot, t}$	0.0308**	0.0219***	0.0146***	0.0085	0.0070	0.0015	0.0021	0.0041	0.0026
	(0.0134)	(0.0075)	(2.5884)	(0.0058)	(0.0074)	(0.0062)	(0.0054)	(0.0038)	(0.0038)
σ_t	−0.1415***	−0.1157***	−0.1022***	−0.1009***	−0.0899***	−0.0640***	−0.0343***	−0.0214**	−0.0032
	(0.0313)	(0.021)	(−7.3030)	(0.012)	(0.0171)	(0.0079)	(0.0095)	(0.0086)	(0.0131)
RH_t	−0.1218	−0.1288	−0.0802	−0.0168	−0.0094	−0.0364	−0.0447	−0.0135	0.0404
	(0.1233)	−0.0870	(−0.8699)	(0.0869)	(0.0702)	(0.0583)	(0.0532)	(0.06)	(0.0788)
RS_t	0.0506	0.0146	−0.0140	−0.0036	0.0337	0.0255	−0.0183	−0.0273	−0.0367
	(0.0477)	(0.0371)	(−0.3287)	(0.0508)	(0.0574)	(0.0431)	(0.0389)	(0.0426)	(0.0356)
$R_{MSCI\_EU, t}$	−0.0247	−0.0428**	−0.0377**	−0.0538***	−0.0313**	−0.0296**	−0.0336***	−0.0230***	−0.0132
	(0.0230)	(0.0174)	(−2.4300)	(0.0136)	(0.0158)	(0.0121)	(0.0107)	(0.0081)	(0.0093)
$VSTOXX_t$	−0.0115***	−0.0163***	−0.0169***	−0.0154***	−0.012***	−0.0086***	−0.0077***	−0.0083***	−0.0064***
	(0.0037)	(0.0027)	(−5.8275)	(0.0029)	(0.0031)	(0.0019)	(0.0017)	(0.0014)	(0.0015)
$R_{IBOXX\_EU, t}$	−0.1505	−0.1468*	−0.1542**	−0.1474**	−0.1646**	−0.1802***	−0.1271**	−0.1553***	−0.1120***
	(0.1149)	(0.0877)	(−2.2655)	(0.0596)	(0.0676)	(0.0637)	(0.0582)	(0.0442)	(0.0421)
$ZC_{Ger, t}$	−0.6086***	−0.4405***	−0.3249***	−0.2268***	−0.1346***	−0.0591***	−0.0268***	−0.0259***	0.0092
	(0.0543)	(0.0329)	(−10.2605)	(0.0279)	(0.0235)	(0.0125)	(0.0082)	(0.0073)	(0.0101)

This table presents the quantile regression estimates for the carbon convenience yield for each quantile considered according to the empirical model defined by Eq. (6). The variables considered are α which denotes the intercept, $R_{Spot, t}$ which is the logarithmic return of the EUA Daily Futures, σ_t represents the Parkinson (1980) volatility proxy of the EUA Futures; RH_t and RS_t are dummy variables that measures the hedging and the speculative pressure, respectively; $R_{MSCI\_EU, t}$ is the logarithmic return of MSCI Europe Index, $VSTOXX_t$ denotes the EURO STOXX50 volatility Index; $R_{IBOXX\_EU, t}$ represents the logarithmic returns of the IBOXX EURO Corporates AAA Index; and $ZC_{Ger, t}$ is the Germany 10-year zero-coupon yield curve. Figures in brackets denote the standard error. The ***, ** and * indicate rejection of the null hypothesis at the 1%, 5% and 10% level, respectively.

significant for all quantiles except for the highest. This negative relationship has also been identified in the carbon literature by Borak et al. (2006), Madaleno and Pinho (2011) and Trück and Weron (2016). However, unlike previous findings, our QR results show that the comovement between the convenience yield and carbon volatility intensifies from the upper to the lower quantiles, indicating that the negative dependence rises in periods of low volatility in carbon markets. A possible explanation for this increase may have to do with the fact that the lower the carbon volatility, the lower the margin rates required when buying carbon futures.

Finally, regarding the proxies to measure the hedging and speculative pressure, we find insignificant dependence across the different quantiles. The lack of statistical significance of the speculative proxy may be surprising given that the front contract series we analyse is the carbon futures contract that concentrates the majority of the speculative activity (see Lucia et al., 2015). In any case, these results suggest that neither the hedging nor the speculative behaviour of carbon traders influences the carbon convenience yield.

4.4.2. Comovement structure between the negative convenience yield and the main benchmarks

The impact of the European stock market return is negative and significant but only for the intermediate levels, whereas for the extreme quantiles we observe no significant effects, confirming the presence of an asymmetric dependence structure, since there is extreme tail independence in the 0.1 and 0.9 quantiles but intermediate dependence. The effect of the European implied volatility (VSTOXX) on the carbon convenience yield is significantly negative at the 1% level in all quantiles, an effect that is more pronounced in the lower volatility quantiles.

The effect of the European AAA corporate bonds is also negative and significant at the conventional levels for all quantiles except for the lowest. We have applied the Wald-test for the equality of coefficients for all quantiles from 0.2 to 0.9. The null of equality cannot be rejected, confirming that all the estimates are uniform across these quantiles. Finally, the effect of the Germany 10-year zero-coupon yield is negative and significant at the 1% level for all quantiles, except for the 0.9 quantile. The comovement between the convenience yield and the Germany 10-year zero-coupon yield intensifies from the upper to the lower quantiles, indicating, as in the case of the VSTOXX, that the dependence increases in periods of low yields.

4.5. Goodness of fit

Finally, we have evaluated the goodness of fit for the QR model. To do so, we have calculated the Pseudo R^2. This index is related to a given quantile and can be used to assess the model with the best goodness of fit among several nested models. The Pseudo R^2 has been obtained as follows:

$$\text{Pseudo } R^2 = 1 - \frac{RASW^{\theta}}{TASW^{\theta}} \tag{9}$$

where, for each considered quantile θ, $RASW_\theta$ is the residual absolute sum of weighted differences between the observed dependent variable and the estimated quantile conditional distribution and $TASW_\theta$ is the total absolute sum of weighted differences between the observed dependent variable and the estimated quantile.[13]

Table 5 presents the estimated Pseudo R^2 of three nested models. Specifically, we have regressed the carbon convenience yields on several factors by applying the QR approach. The first model we have estimated is a QR model that considers only variables related to the carbon model ($R_{Spot, t}$, σ_t, RH_t and RS_t). The second one considers the carbon-related variables and the US benchmarks ($R_{MSCI\_USA, t}$, VIX_t, $R_{IBOXX\_USA, t}$ and $ZC_{USA, t}$). The third one includes the carbon-related variables and the European benchmarks ($R_{MSCI\_EU, t}$, $VSTOXX_t$, $R_{IBOXX\_EU, t}$ and $ZC_{Ger, t}$).

The Pseudo R^2 values of models II and III are higher than those for model I for each quantile, with the Pseudo R^2 values of the model III being the highest. Therefore, the comparisons between the corresponding Pseudo R^2 of the nested models I and II, on the one hand, and I and III, on the other hand, confirm that it is advantageous to move from the model that only considers carbon-related variables to more complex models.

5. Conclusions

This paper has investigated the influence of carbon market variables on the negative convenience yield but, unlike previous papers, we have also studied the relationship between the negative convenience yield, the

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[13] See Davino et al. (2013, pp.117-119) for a detailed description of the estimation of this measure.

Table 5
Goodness of fit.

Pseudo R^2	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
Model I: Carbon	6.59	7.37	5.76	3.97	1.94	1.04	0.41	0.24	0.04
Model II: Carbon + US	13.11	12.88	10.25	7.36	4.16	2.31	1.09	0.81	0.64
Model III: Carbon + EUR	21.43	20.56	16.60	11.84	6.54	3.38	1.60	1.73	0.51

This table presents the Pseudo R^2 expressed in percentage for three QR models. The first one is the QR model that considers only variables related to the carbon model ($R_{Spot,\ t}$ σ_t, RH_t and RS_t). The second one considers the carbon-related variables and the US benchmarks ($R_{MSCI\_USA,\ t}$, VIX_t, $R_{IBOXX-USA,\ t}$ and $ZC_{USA,\ t}$). The third one includes the carbon-related variables and the European benchmarks ($R_{MSCI-EU,\ t}$, $VSTOXX_t$, $R_{IBOXX\_EU,\ t}$ and $ZC_{Ger,\ t}$).

inconvenience yield and other financial assets that exhibit negative or null correlation with the price of the emission rights. Furthermore, we have analysed the comovement between the negative convenience yield and the conditioning variables using a quantile regression approach that provides specific insights into the impacts of carbon and non-carbon-related variables on the convenience yield under different market scenarios, such as bearish and bullish markets.

Our empirical results indicate that some carbon trading variables, such as the carbon spot price and volatility, are behind this contango situation, especially when the carbon market is bearish, or its volatility is low. However, we have shown that the carbon inconvenience yield is better explained if other financial markets and variables are also considered, such as benchmarks from equity markets, fixed income markets and sovereign bonds.

Our findings support the idea that portfolio managers and passive investing, carried out by Exchange Trade Funds, may be responsible for the long positions taken in EUA carbon futures. Indeed, the pressure exerted by the financialization of the European Carbon Futures Market on the demand for EUA futures to diversify or hedge their investments linked to broad market indices would lead to EUA futures prices being traded at a relative premium that would be collected not only by the carbon warehousers, but also by financial institutions that might offer their clients financial products to profit from the contango situation in exchange for a commission. This pressure would last until the supply of EUAs in the spot market was exhausted or until the sale of more EUA futures contracts was disincentivised due to the initial and variation margin rates charged by the EUA futures market. These limits on cash and carry arbitrage operations would contribute to maintaining the systematic inconvenience yield observed in the European Carbon Futures Market since 2009.

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Appendix A. Supplementary data

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