Journal of Commodity Markets 29 (2023) 100310

Contents lists available at ScienceDirect

Journal of Commodity Markets

journal homepage: www.elsevier.com/locate/jcomm

Regular article

Theory of storage implications in the European natural gas market[☆]

Beatriz Martínez[a], Hipòlit Torró[b,*]

[a] Department of Business Finance at the Universitat de València, Spain
[b] Department of Financial and Actuarial Economics at the Universitat de València, Spain

ARTICLE INFO

Keywords:
Convenience yield
Natural gas
Futures markets

ABSTRACT

The theory of storage stands that futures prices should be equal to the spot price plus the interest forgone in storing the commodity and the warehousing costs minus the convenience yield on the inventory. In this paper, we test several implications of the theory of storage on the pricing of United Kingdom natural gas futures. We obtain partial evidence for the theory of storage as a complete explanation of the pricing of this futures contract. Explicitly, (i) we obtain evidence to explain convenience yield seasonality with spot price volatility, unexpected demand shocks when supply is tight, inventory variations, and trading activity in the futures markets; (ii) we obtain indirect evidence for the theory of storage in accepting the Samuelson hypothesis; (iii) weak although significant influence of storage levels in determining the basis is obtained; (iv) we find weak evidence for the inventory influence of futures volatility; and (v) finally, the slope of the convenience yield structure is found to respond to inventory changes and trading activity in the futures markets that anticipates inventory scarcity. All in all, we can conclude that our evidence for the theory of storage in this market is strong but cannot completely explain futures pricing for natural gas.

1. Introduction

The convenience yield, the marginal benefit to the holders of adding an extra unit of stock in storage, was introduced by the theory of storage to relate current and futures prices of storable commodities. Specifically, the theory of storage states that the futures price of a storable commodity must be equal the spot price plus all the costs and minus the benefits of storing this commodity until futures maturity. When inventories are high, the marginal yield of adding an extra unit of stock to the inventory is very low or zero. In this situation, futures and spot prices are perfectly tied through the cost of carry, otherwise a cash and carry arbitrage (direct or reverse) will be executed until this relationship is re-established. But when storage levels are low, the convenience yield can take high values to produce futures prices below spot prices (Working (1949), Kaldor (1939) and Brennan (1958)). In this case, arbitrage will be difficult because of commodity scarcity. This is especially true for reverse cash and carry because this arbitrage might imply a stockout whose cost might be higher for the stockholder than any benefit coming from the arbitrage strategy. Moreover, unlike financial assets,

---

[☆] Financial support from the Spanish Ministry of Science and Innovation and ERDF is gratefully acknowledged (Grant PGC 2018-093645-B-100 funded by MCIN/AEI/10.13039/501100011033 and by “ERDF A way of making Europe"). We also wish to thank Angel Pardo for his comments. All errors are our own responsibility.

[*] Corresponding author. Facultat d’Economia, Universitat de València, Avda. dels Tarongers s/n, 46022, València, Spain.
E-mail address: hipolit.torro@uv.es (H. Torró).

https://doi.org/10.1016/j.jcomm.2022.100310
Received 3 March 2021; Received in revised form 14 September 2022; Accepted 23 December 2022

commodity stock inventory levels have a non-negative constraint.

Natural gas futures pricing can deviate from the cost of carry pricing. Duffie (1989, p. 98) points out that there are few assets that adhere exactly to the theory of storage since storage costs, interest rates, and convenience yield until delivery are sometimes uncertain and transaction costs may be significant. Specifically, in the case of UK natural gas futures contracts, Cartea and Williams (2008) offer several explanations for the difficulty of cash-and-carry pricing. During winter cold snaps, the rates at which gas can be injected or withdrawn from storage systems are limited and cannot stop a rise in stock prices. Cartea and Williams (2008) observe that limitations in the withdrawal capacity of the system limits the possibility of taking advantage of rising prices. Consequently, the direct application of the cost of carry pricing to exploit arbitrage opportunities is not as clear as the theory would suggest. Therefore, the net convenience yield, as it is usually computed (negative relative basis plus interest yield until the futures maturity), can include the friction effect of some disconnection between spot and futures prices. Nevertheless, excluding some specific situations of high demand or supply interruptions, natural gas suppliers will benefit by having stocks because it enables them to optimise marketing costs and avoid stockouts.

Further to the above specific characteristics of natural gas markets, Volmer (2011) argues several reasons why results obtained for other storable commodities are not applicable to natural gas: (i) transportation costs for gas are much higher, and as pipelines are still the dominant medium for gas distribution this can lead to persistent demand-supply imbalances when the capacity limit of the pipeline system is reached and this will be visible in regional price differences; (ii) short-term futures prices exhibit spikes, which are mostly due to the role of gas as a back-up energy source because natural gas-fired generation plants can rapidly ramp output in response to variable output from renewable sources; and (iii) storage technologies for gas are complex and costly since gas is stored underground.

To test the implications of the theory of storage in the European natural gas futures markets, we need to carefully study the fundamental variables explaining convenience yield. Fundamental variables used in the bibliography are inventory levels, demand, and the spot price volatility. Further to this, we introduce futures market liquidity measured with the open interest as a variable containing important information about the projected scarcity or excess of commodity inventories.

Inventory level is the variable most closely related to the convenience yield. Inventory level plays a central role in explaining the inter-temporal relationship linking current demand and supply to expectations of future demand and supply (Pindyck, 2001; Alquist et al., 2014). Storing natural gas provides operational flexibility to natural gas suppliers and helps them to avoid stockout. It makes sense to think that optimal levels of supply and inventories are jointly determined, given the spot price, the futures prices, and the price of storage (Pindyck, 2001). Natural gas storage levels depend on several factors. For example, the rate of injection and withdrawal: higher rates imply higher costs of storage. Further to capacity restrictions on stock inflow and outflow, time lags between withdrawal to delivery, and total capacity restriction produce deviations from the expected seasonal inventory values. Demand for natural gas has a clear seasonal pattern as it peaks in winter when natural gas is burned for heating. Weather variables based on temperature are used to proxy seasonal demand for natural gas. Unexpected cold snaps can produce increases in demand for natural gas and raise natural gas prices. In this situation, volatility of spot prices may increase (see Mu (2007)), and the value of a stored commodity will be higher. The convenience yield will reflect the strategic value of inventories. Finally, liquidity in the futures markets can help us to further understand the pricing formation process of this futures contract. In this market, the liquidity of all futures contracts increases in the months before winter because many strategies are implemented during the summer season to hedge the price risk of natural gas in the reservoirs to attain unexpected demand shocks during the winter season.

The purpose of this paper is to test several implications of the theory of storage in the UK natural gas market and establish to what extent this approach for futures pricing is valid in this market. This study updates previous tests and completes them by incorporating novel concepts and analytical tools. The novel concept of rollover convenience yield or accrued convenience yield in the front contract is an alternative measure to the convenience yield since the front futures contract is the contract with the highest traded volume and many agents prefer to implement their strategies using this contract because of its greater liquidity. The difference between both measures will define a term risk-premium that will be shown to indicate future scarcity or excess of inventory of the commodity. Moreover, the convenience yield term structure is analysed for the first time in the British natural gas market and this throws light on how convenience yield responds to changes in storage levels. Finally, we uncover that activity in futures markets helps to explain the seasonal behaviour of the term risk-premium and movements in the slope of the term structure of the convenience yield. Unexpected changes in the perception of future risky situations in the spot market are disclosed with changes in futures positions when hedging strategies are modified.

In the following section, the methodology used to define the main variables used in this study is presented. In section 3 we present the data set and describe the main features of the convenience yield and related variables. In Section 4, we propose several tests of direct and indirect implications of the theory of storage on futures pricing in the UK natural gas market. Finally, we conclude with a summary of the main results of our sets of tests and some implications for agents involved in this market.

2. Methodology

The convenience yield is approximated following Wei and Zhu (2006),

$$CY(t-j,t)=\left(1+R(t-j,t)\times\frac{j}{12}\right)\times S(t-j)-F(t-j,t) \qquad [1]$$

Where $CY(t-j,t)$ represents the convenience yield for a futures contract j months before its maturity in t, $R(t-j,t)$ is the monthly average rate of the 3-month LIBOR in pound sterling, $S(t-j)$ is the system average price in $t-j$ and $F(t-j,t)$ is the futures price in $t-j$

for a contract maturing in t and time is measured in months, $j = 1, 2, 3, \dots$ This proxy is known in the literature as the marginal convenience yield net of storage costs. That is, the genuine convenience yield minus storage costs without exactly separating its components. Convenience yield is not an observable variable and storage costs are difficult to obtain and depend on many factors such as location, state of the infrastructure, injection and withdrawal costs, etc. Similar proxies, without considering estimations on storage costs, are used in Fama and French (1987) and Geman and Ohana (2009).

In most futures markets, the most liquid futures contract is the front contract, that is the futures contract closest to maturity. As Martínez and Torró (2018) show, the front contract is the most liquid of all the UK natural gas futures contracts traded in the ICE. Furthermore, these authors also show that front month contracts also have lower transaction costs compared to the remaining futures contract maturities (taking into account bid-ask spreads and the fees involved). Larger liquidity and lower transaction costs lead agents to trade in the front contract when implementing futures strategies for terms longer than front futures contract maturity by performing a trade known as a rollover. That is, when the front contract is about to expire the positions in this contract are closed and simultaneously opened on the second contract nearest to maturity. This trading continues until the desired term is attained. This strategy can be compared to trading in a long-term futures maturity that exactly fits the desired planning horizon, to evaluate if agents prefer to invest in shorter terms with greater liquidity or in longer terms that exactly match their investment objective. Inspired by Alquist et al. (2014) and Szymanowska et al. (2014), we apply the expectations hypothesis to express the convenience yield in long term futures contracts as the accrued expected convenience yield in the front contract plus a term risk-premium,

$$CY(t-j,t) = \sum_{i=0}^{j-1} E_{t-j}[CY(t-j+i, t-j+i+1)] + RP(t-j,t) \qquad [2]$$

with $j > i$. To obtain an ex post estimate of the above equation, we take rational expectations. Therefore, long term convenience yield is decomposed as the accrued realised front contract convenience yield plus the realised term risk-premium. We will call Rollover Convenience Yield (*ROCY*) to the accrued realised front contract convenience yield net of storage costs in a rollover strategy. That is,

$$ROCY(t-j,t) = \sum_{i=0}^{j-1} CY(t-j+i, t-j+i+1) \qquad [3]$$

with $j > i$. Finally, realised term risk-premium will be computed as the difference between the conventional convenience yield and the rollover convenience yield

$$RP(t-j,t) = CY(t-j,t) - ROCY(t-j,t) \qquad [4]$$

with $j > 1$. The theory of storage says that short-term convenience yield is related to the current level of inventories and the convenience yield implied in long-term maturity futures prices contains information about the expected changes in inventories and the expected commodity scarcity. Therefore, the term risk premium defined in Equation (4) will indicate (if positive) how much buying agents in long-term futures maturity are willing to pay to avoid commodity scarcity in the future.

3. Data

In this study we focus on the British natural gas market. The British natural gas market is the oldest and most liberal natural gas market in Europe. We chose the national balancing point (NBP) because is the most liquid UK natural gas hub and its futures contract, traded at The ICE, is a European benchmark (see Schultz and Swieringa, 2013). Restricted by storage data availability, we use monthly time series frequency. We use monthly spot and futures prices for the National Balancing Point for the period from April 2000 to August 2020. Futures prices and open interests are obtained directly from the Intercontinental Exchange and 1–6 months to maturity futures contracts are used to avoid liquidity problems. Monthly time series are built by taking closing prices on the day prior to the last trading day of the front contract – avoiding in this way the 'last trading day' turbulences in the front contract. The monthly open interest dataset is calculated as the daily open interest average for each month. The system average price (SAP henceforth) is used as spot price. The SAP is the reference price used by the National Grid for balancing incorporates weighted average prices of all trades for a specific delivery day on the balancing market called 'On-the-day Commodity Market (OCM)'. This is the average price of all gas traded through the balancing market. Market participants post bids or offers for volumes of gas as day-ahead and within-day trades. The SAP aggregates the trades conducted on the On-the-Day Commodity Market (OCM). This is the market that the National Grid uses in its role as residual balancer, although other markets exist for wholesale gas trading in GB. As stated for the National Grid and the Office for National Statistics, while these prices reflect spot prices on the day, they should be treated with caution as these can be subject to extreme within-day trading and this may skew actual traded prices.[1] The daily SAP is used to determine the futures price and is therefore a useful indicator of supply constraints and demand pressures and may be used to understand the general trend for gas prices within Great Britain. The OCM is operated by the ICE Endex exchange, as appointed by National Grid in its capacity as transmission system operator.

Data on storage comes from the Joint Organizations Data Initiative in the International Energy Agency website. We decided to employ the IEA-JODI natural gas data because it is the longest European natural gas storage data series. The data provided by Reuters is

---

[1] https://www.ons.gov.uk/economy/economicoutputandproductivity/output/datasets/systemaveragepricesapofgas. Last accessed: September 2022.

from Gas Infrastructure Europe (GIE) but GIE changed its methodology for storage data, so it was impossible to continue the historical time series. The National Grid also provides storage data for the UK, but this time series is shorter than IEA-JODI data.

Table 1 provides the description of the data sources. To approximate demand, we use weather variables, specifically heating degree days in the United Kingdom and deviations from its historical average value for each month. The Heating Degree Days and LIBOR are from European Commission and European Central Bank respectively. We use LIBOR 3-month rates because after some manipulation problems, the Bank of England and European Central Bank stopped supplying the LIBOR 1-month rate data, so only the 3-month rate was available. To have the same maturity for the futures and the rest of the data we took the 3-month rate and adjusted it using j/12, being j the time to maturity of the futures contract.

In Fig. 1 we can observe that at the beginning of March 2018 the largest price spike in the history of natural gas prices occurred. This is due to several factors, such as a cold spell along with historic low storage levels as a result of the permanent decommissioning of the Rough storage facility and some supply infrastructure outages. Rough, the largest and oldest British storage facility, ceased to be functional in June 2017 and was being emptied throughout winter 2017–2018 until its complete closure in 2018, as can be observed in Fig. 2 where closing stocks in the UK decrease from 2018. Nevertheless, the lowest levels of storage in the sample are in March 2013 when the UK-Belgian interconnector was halted due to a technical fault. At that time, stored gas was already at a minimum due to a prolonged cold snap. The British government has not replaced the Rough natural gas storage facility as the goal is to convert the energy system to renewable sources by 2020. As Britain is far from achieving that aim and gas accounted for most heating and power generation, imports of LNG have increased dramatically in recent years, compensating somehow for the traditional underground natural gas storage.

To obtain comparable results to the conventional convenience yield we will consider rollover strategies for maturities ranging from 2 to 6 months. Table 2 presents the descriptive statistics for the conventional convenience yield, the rollover convenience yield and the difference between these both variables, see Equations (1), (3) and (4) in section 2, respectively. A descriptive analysis of the convenience yield net of storage costs is reported in Fig. 3 and Table 2 Panel A. Specifically, in Fig. 3 it can be seen that convenience yield is greater in winter than in summer and their values increase as maturity increases. Table 1 Panel A shows that convenience yields reach their lowest values for the summer months just when storage is increasing and is nearly at its highest values. The highest values correspond to the winter months, just when reservoir levels begin to decrease and reach their lowest values. Furthermore, all mean values are significantly different from zero and winter mean values and volatilities are significantly higher than summer mean values and volatilities for the six studied maturities. We obtain that rollover convenience yield (see Table 2, Panels B) is significant and positive, higher in winter to summer although the difference between mean values in both seasons is not statistically significant. Nevertheless, winter volatility is significantly above the summer volatility for the rollover convenience yield. The term risk-premium measured the difference between the conventional convenience yield and the rollover convenience yield is reported in Table 2 Panel C. The most interesting results are obtained when the mean for the winter and summer is analysed. The mean value and monthly mean values are mostly not significant, but seasonal mean values are significant and positive in winter and negative in summer with absolute values increasing with the time to maturity. Therefore, the first intuition in this result is that natural gas futures maturing in winter months incorporate a higher convenience yield to avoid scarcity in that season. This computation for the summer months is negative and indicates how much agents are willing to pay to avoid an excess of inventories in the summer season.

4. Testable implications of the theory of storage

This is the core section of the paper. Here we design several tests to check if some of the implications of the theory of storage can be sustained for natural gas futures contracts in the UK market. These tests are grouped in five subsections.

1. Seasonal pattern in the convenience yield.
2. Relative basis should vary one-for-one with interest rate.
3. Samuelson effect.
4. Negative relationship between price volatility and inventories.
5. Convenience yield term structure.

Table 1
Data description.

Variable	Description	Unit	Source
System average price (SAP)	Average price of all gas traded via the on-the-day commodity market (OCM) mechanism for the gas day in UK	pence/therm	National Grid/Reuters
Futures prices	National Balancing Point (NBP) futures price for 1–6 months	pence/therm	Intercontinental Exchange (ICE)
Open interest	Open interest at the close of business on a trading day	Number of contracts	Intercontinental Exchange (ICE)
Heating degree days (HDD)	HDD for each month in UK	Degrees Celsius	European Commission: Agri4Cast Data Portal
Storage	Closing stocks: stock level held on the UK national territory on the last day of the reference month	Terajoules (TJ)	International Energy Agency, JODI Initiative
LIBOR	3-month interest rate; period average	Percent per annum	European Central Bank

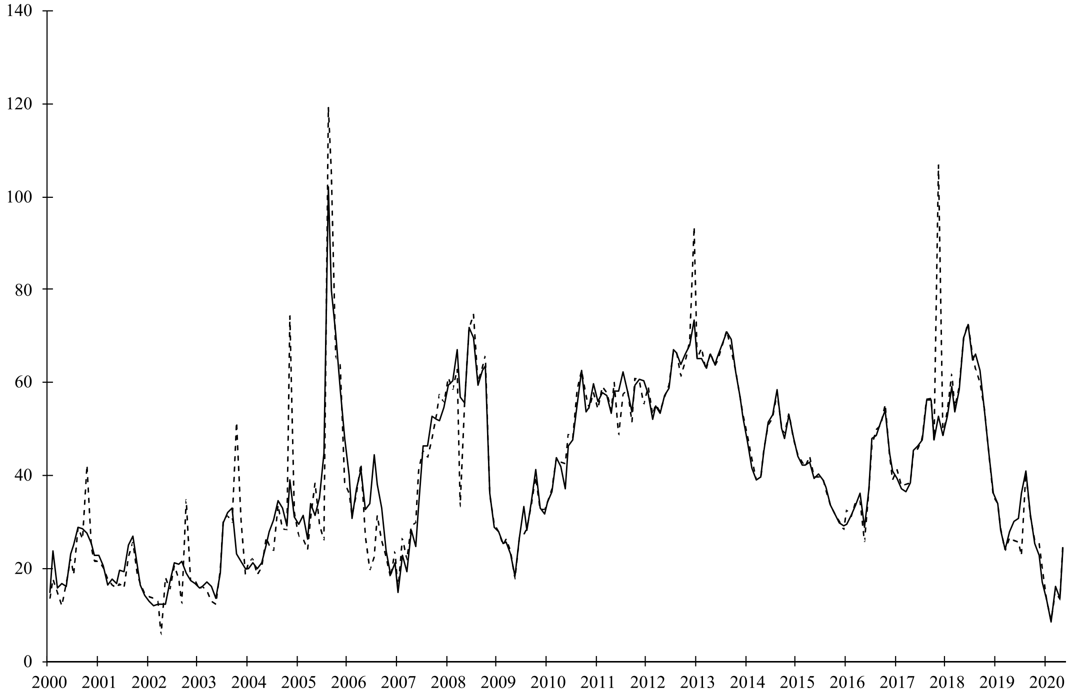

Fig. 1. NBP spot and futures natural gas prices (pence/therm) Spot price (- - -) and the first to 'delivery' futures price (——).

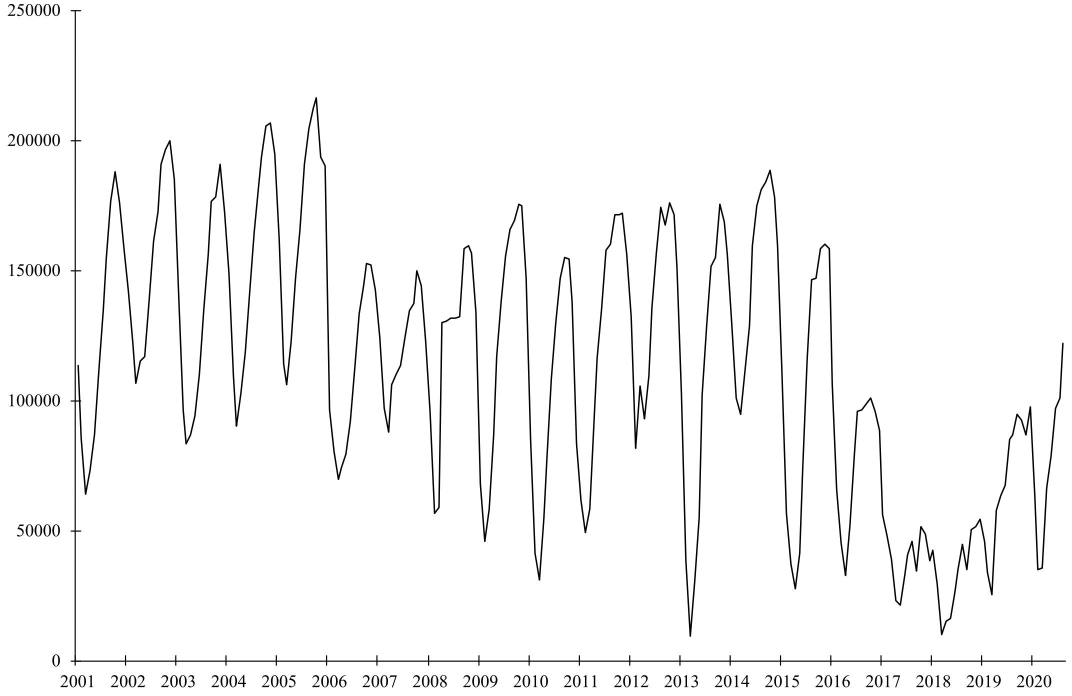

Fig. 2. Natural gas storage levels (terajoules).

4.1. Seasonal pattern in the convenience yield

Fama and French (1987) tested the following hypothesis of the theory of storage: 'Seasonal in production or demand can generate seasonal in inventories. Under the theory of storage, inventories seasonals generate seasonals in the marginal convenience yield and, then in the basis'. Evidence of the seasonality in the basis was obtained for agricultural commodities. This is indirect evidence of the

Table 2

Descriptive statistics for the convenience yield and the rollover convenience yield. Taking monthly frequency data from April 2000 until August 2020 (245 observations) *convenience yields* are reported in Panel A. Convenience yield is computed following Wei and Zhu (2006) as $CY(t-j,t) = \left(1+LIBOR\times\frac{j}{12}\right)\times S(t-j) - F(t-j,t)$ where *LIBOR* is the 3-month LIBOR average rate, $S(t-j)$ is the system average price in $-j$, and $F(t-j,t)$ is the futures price in $t-j$ for a contract maturing in t. In Panel B, results for the rollover convenience yields computed as $ROCY(t-j,t) = \sum_{i=0}^{j-1} CY(t-j+i, t-j+i+1)$; $j = 2,3,4,5,6$; are reported. In Panel C, results on the difference between both variables, computed as $RP(t-j,t) = CY(t-j,t) - ROCY(t-j,t)$; $j = 2,3,4,5,6$; are reported. Mean values and their *p*-value for the *t*-statistic mean zero hypotheses tests are reported between brackets. Winter season is defined by taking the following months: October, November, December, January, February and March. For summer season, the remaining months are taken. In 'Mean equality', 'Median equality' and 'Variance equality' rows, the *t*-statistic, the *Kruskal-Wallis* and the *Levene* test statistics and their *p* values in brackets are reported.

	Panel A. Convenience yield					
	1 months	2 months	3 months	4 months	5 months	6 months
Whole period	7.19 [0.00]	12.72 [0.00]	18.37 [0.00]	24.44 [0.00]	37.91 [0.00]	37.26 [0.00]
January	11.38 [0.00]	21.32 [0.00]	32.14 [0.00]	42.27 [0.00]	60.47 [0.00]	60.47 [0.00]
February	13.54 [0.00]	23.56 [0.00]	32.57 [0.00]	41.37 [0.00]	57.43 [0.00]	56.71 [0.00]
March	6.64 [0.00]	13.82 [0.00]	20.52 [0.00]	26.53 [0.00]	38.13 [0.00]	38.05 [0.00]
April	6.15 [0.00]	12.33 [0.00]	17.97 [0.00]	23.00 [0.00]	34.74 [0.00]	30.33 [0.00]
May	6.35 [0.00]	11.52 [0.00]	16.39 [0.00]	22.19 [0.00]	29.72 [0.00]	21.97 [0.01]
June	5.75 [0.00]	10.06 [0.00]	15.62 [0.00]	16.88 [0.00]	21.01 [0.01]	16.70 [0.04]
July	3.49 [0.01]	8.45 [0.00]	9.14 [0.00]	7.13 [0.05]	13.75 [0.02]	11.52 [0.04]
August	6.84 [0.00]	8.13 [0.01]	6.56 [0.07]	8.78 [0.07]	18.84 [0.01]	19.21 [0.01]
September	5.51 [0.03]	5.38 [0.18]	7.99 [0.17]	12.54 [0.10]	27.53 [0.02]	31.07 [0.01]
October	3.58 [0.20]	6.30 [0.19]	10.32 [0.13]	18.19 [0.04]	37.05 [0.01]	41.62 [0.00]
November	9.62 [0.01]	16.37 [0.01]	25.79 [0.00]	38.31 [0.00]	62.24 [0.00]	64.65 [0.00]
December	7.77 [0.03]	16.02 [0.01]	26.69 [0.00]	38.33 [0.00]	57.54 [0.00]	59.10 [0.00]
Winter	8.75 [0.00]	16.23 [0.00]	24.67 [0.00]	34.17 [0.00]	52.14 [0.00]	53.43 [0.00]
Summer	5.69 [0.00]	9.34 [0.00]	12.31 [0.00]	15.11 [0.00]	24.24 [0.00]	21.72 [0.00]
Mean equality	2.18 [0.03]	2.94 [0.00]	3.71 [0.00]	4.41 [0.00]	4.42 [0.00]	5.01 [0.00]
Median equality	0.47 [0.49]	4.48 [0.03]	13.05 [0.00]	24.06 [0.00]	26.97 [0.00]	36.84 [0.00]
Winter volatility	13.95	22.75	31.85	41.29	60.01	60.73
Summer volatility	7.17	12.65	18.75	24.63	36.23	35.63
Variance equality	17.56 [0.00]	18.04 [0.00]	16.65 [0.00]	17.57 [0.00]	16.12 [0.00]	17.41 [0.00]

	Panel B. Rollover convenience yield				
	2 month	3 months	4 months	5 months	6 months
Whole period	11.82 [0.00]	17.50 [0.00]	23.69 [0.00]	37.26 [0.00]	36.81 [0.00]
January	17.03 [0.00]	24.74 [0.00]	28.78 [0.00]	45.51 [0.00]	41.35 [0.00]
February	18.85 [0.00]	26.04 [0.00]	33.54 [0.00]	44.83 [0.00]	44.79 [0.00]
March	17.31 [0.00]	25.55 [0.00]	32.05 [0.00]	45.13 [0.00]	44.76 [0.00]
April	16.29 [0.00]	22.78 [0.00]	30.50 [0.00]	43.70 [0.00]	40.55 [0.00]
May	12.05 [0.00]	20.95 [0.00]	28.45 [0.00]	37.49 [0.00]	35.57 [0.00]
June	10.77 [0.00]	17.62 [0.00]	21.95 [0.00]	32.10 [0.00]	33.01 [0.00]
July	10.22 [0.00]	11.46 [0.00]	15.61 [0.00]	28.35 [0.00]	29.76 [0.00]
August	6.05 [0.01]	8.65 [0.01]	13.69 [0.00]	25.66 [0.00]	28.73 [0.00]
September	5.59 [0.07]	9.07 [0.02]	14.27 [0.00]	29.52 [0.00]	31.08 [0.00]
October	6.25 [0.12]	9.62 [0.05]	16.94 [0.01]	33.13 [0.00]	34.09 [0.00]
November	7.98 [0.03]	15.67 [0.01]	22.14 [0.00]	40.88 [0.00]	35.54 [0.00]
December	13.91 [0.00]	18.65 [0.00]	27.31 [0.00]	41.35 [0.00]	42.43 [0.00]
Winter	13.56 [0.00]	20.04 [0.00]	26.79 [0.00]	41.81 [0.00]	40.50 [0.00]
Summer	10.15 [0.00]	15.03 [0.00]	20.64 [0.00]	32.75 [0.00]	33.12 [0.00]
Mean equality	1.81 [0.07]	1.82 [0.07]	1.72 [0.08]	0.00 [0.09]	0.00 [0.16]
Median equality	0.97 [0.32]	1.33 [0.25]	2.04 [0.15]	1.65 [0.20]	1.29 [0.26]
Winter volatility	16.90	24.37	30.83	44.77	44.05
Summer volatility	12.19	17.98	24.30	36.78	36.68
Variance equality	9.86 [0.00]	8.55 [0.00]	5.36 [0.02]	4.76 [0.03]	2.82 [0.09]

	Panel C. Term risk-premium				
	2 month	3 months	4 months	5 months	6 months
Whole period	0.89 [0.18]	0.82 [0.39]	0.69 [0.61]	0.62 [0.72]	0.39 [0.86]
January	4.28 [0.15]	7.41 [0.03]	13.50 [0.00]	14.96 [0.01]	19.12 [0.01]
February	4.71 [0.25]	6.52 [0.23]	7.83 [0.27]	12.60 [0.14]	11.92 [0.29]
March	−0.54 [0.48]	−4.89 [0.05]	−6.72 [0.01]	−8.77 [0.01]	−14.98 [0.01]
April	−4.04 [0.05]	−5.05 [0.02]	−7.82 [0.01]	−9.37 [0.02]	−10.80 [0.03]

(*continued on next page*)

Table 2 (*continued*)

	Panel C. Term risk-premium				
	2 month	3 months	4 months	5 months	6 months
May	−0.54 [0.48]	−4.89 [0.05]	−6.72 [0.01]	−8.77 [0.01]	−14.98 [0.01]
June	−1.77 [0.33]	−2.32 [0.37]	−8.48 [0.03]	−15.18 [0.00]	−18.94 [0.01]
July	−1.77 [0.33]	−2.32 [0.37]	−8.48 [0.03]	−15.18 [0.00]	−18.94 [0.01]
August	2.08 [0.11]	−2.09 [0.19]	−4.91 [0.08]	−6.82 [0.01]	−10.81 [0.03]
September	−0.21 [0.89]	−1.09 [0.70]	−1.73 [0.67]	−2.00 [0.66]	−0.01 [1.00]
October	0.04 [0.98]	0.70 [0.79]	1.25 [0.76]	3.92 [0.45]	7.53 [0.17]
November	8.39 [0.02]	10.12 [0.08]	16.17 [0.04]	21.36 [0.03]	29.11 [0.05]
December	2.11 [0.41]	8.04 [0.03]	11.02 [0.08]	16.19 [0.04]	16.67 [0.04]
Winter	2.68 [0.02]	4.63 [0.01]	7.37 [0.00]	10.34 [0.00]	12.94 [0.00]
Summer	−0.84 [0.14]	−2.89 [0.00]	−5.88 [0.00]	−9.01 [0.00]	−12.16 [0.00]
Mean equality	2.73 [0.01]	4.05 [0.00]	5.14 [0.00]	6.05 [0.00]	5.95 [0.00]
Median equality	4.19 [0.04]	18.55 [0.00]	40.94 [0.00]	67.59 [0.00]	70.52 [0.00]
Winter volatility	12.81	18.23	25.10	31.15	40.49
Summer volatility	6.37	9.42	13.29	16.19	22.33
Variance equality	10.26 [0.00]	7.43 [0.00]	6.36 [0.01]	6.38 [0.01]	3.99 [0.04]

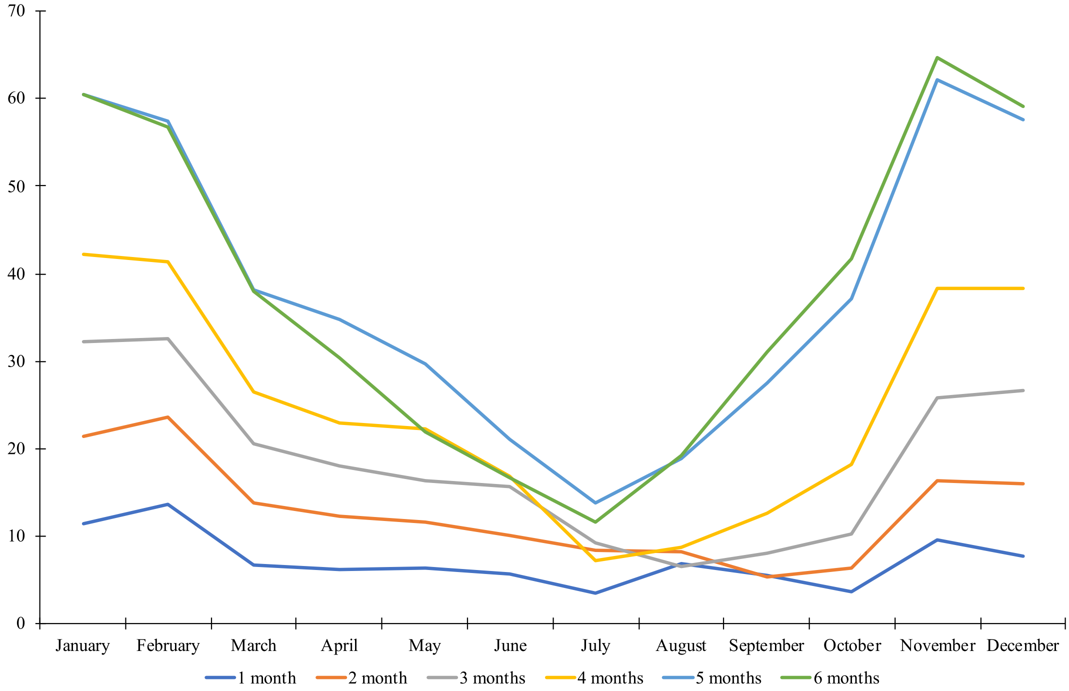

Fig. 3. Monthly average convenience yield for 1–6 month futures maturity (pence/therm).

implication of theory of storage on the existence of a seasonal pattern in agricultural commodity convenience yields. For natural gas in the US, Suenaga et al. (2008) argue that strong seasonality in storage and demand implies that the cost of carry is seasonal and so the basis for consecutive maturities are seasonal. Furthermore, Geman and Ohana (2009) obtained evidence for a close relationship between inventories and convenience yield. Following Campbell and Diebold (2005) we fitted a sinusoidal function to UK inventories and obtained a 93 per cent of determination coefficient for natural gas inventories. When this methodology is fitted to the convenience yield, determination coefficients steadily increase from 12% to 28% when futures maturities vary from 1 to 6 months. Following Geman and Ohana (2009) we have calculated detrended inventories and we have regressed this variable on the convenience yield, but we have not obtained any significant relationship. In the same way, non-detrended inventory levels have a very small explicative power on the convenience yield. Therefore, seasonality in the convenience yield is not a direct result of inventory seasonality nor a deviation of its levels from this seasonal pattern. Nevertheless, seasonality in the convenience yield exists and probably is caused by other variables related to demand or unexpected shocks in demand. Specifically, we will see that for unexpected demand shocks in winter, and higher volatility in winter, trading activity in futures markets and inventory variations can partially explain convenience yield.

As reported in Martínez and Torró (2015) natural gas volatility is seasonal: higher in winter and lower in summer. This seasonality is closely related with demand shocks and storage levels. The relationship between convenience yield and volatility is related with the value of the natural gas in the reservoirs in winter when unexpected demand shocks are frequent and add value to the commodity inventory. As explained in Martínez and Torró (2018), seasonality in energy prices during the year is mainly caused by weather seasonality and its effects on energy demand, especially when supply is tight (see Bessembinder and Lemmon (2002), Longstaff and Wang (2004) and Cartea and Villaplana (2008)). Tight conditions in supply can be identified with decreasing or low storage levels. We put all these conditions together in a variable. That is, we obtain an indicator of demand shocks in tight conditions. A similar indicator was used in Furio and Meneu (2010) to explain risk premium dynamics in Spanish electricity markets using unexpected shocks in demand whenever the level of expected hydroelectricity energy capacity is below its historical mean value.

Inventory decisions are important for commodities because they link current and expected commodities (Routledge et al. (2000)). Convenience yield is expected to be negatively related with inventory variations. We tested that monthly inventory variations have a negative and significant correlation with the convenience yield. This correlation varies around −20% (−17.31%, −21.84, −24.89, −26.36, −24.77, −25.56; for 1 to 6-month futures maturities, respectively).

Finally, trading activity in futures markets may be an indicator of future scarcity of the commodity, and may therefore contain information about the convenience yield. Specifically, in the natural gas spot market, inventory levels increase in summer because demand and prices are lower than in winter. When reservoirs are replenished, the owner of the gas in the inventory assumes an important price risk because it will be stocked until the winter to attain peak demand. This is why in the summer months the average open interest reaches its highest values and the lowest values are reached in the winter months. Fig. 5 reports the monthly average open interest for the six futures contracts considered in this study and visually confirms the differences in futures trading activity across seasons.

The following model we propose relates convenience yields with inventory variations, demand shocks in tight conditions, volatility, and open interest:

$$CY(t-j,t) = a + bSD(t-j) + cUWD(t-j) + dDUK(t-j) + OI(t-j) + \varepsilon(t-j,t) \qquad [5]$$

for j = 1, 2, 3, 4, 5 and 6 months to delivery. $CY(t-j,t)$ represents the marginal convenience yield net of storage costs for a futures contract j months before its maturity in t, see Equation (1). *SD* refers to the standard deviation within each month of the daily system average price. *DUK* refers to natural gas reservoir level changes in the United Kingdom. *UWD* represents, for winter months, the product between *UHDD* with *DUK* when *DUK* is negative. The *UHDD* variable measures the difference between the historical value and the observed daily-accrued heating degree-day for each month within the year for the United Kingdom. Finally, $OI(t-j)$ defines the sum of the monthly open interest for the six futures contracts considered in this study.

Table 3

Regression of convenience yield, rollover convenience yield in the front contract, and the difference between them on the same explicative variables, This table reports the estimation results of the following regressions: Panel A $CY(t-j,t) = a + bSD(t-j) + cUWD(t-j) + dDUK(t-j) + eOI(t-j) + \varepsilon(t-j,t)$.Panel B $ROCY(t-j,t) = a + bSD(t-j) + cUWD(t-j) + dDUK(t-j) + eOI(t-j) + \varepsilon(t-j,t)$.Panel C $RP(t-j,t) = a + bSD(t-j) + cUWD(t-j) + dDUK(t-j) + eOI(t-j) + \varepsilon(t-j,t)$ for $j = 1, 2, 3, 4, 5$ and 6 months to delivery. $CY(t-j,t)$, $ROCY(t-j,t)$, and $RP(t-j,t)$ variables are defined in Table 2. *SD* refers to the standard deviation within each month of the daily system average price. *UWD* represents for winter months the *UHDD* product with *DUK* when *DUK* is negative. The *UHDD* variable measures the difference between the historical value and the observed daily-accrued heating degree-day for each month within the year for the United Kingdom. *DUK* refers to the natural gas reservoir level changes in the United Kingdom. $OI(t-j)$ represents the sum of the monthly open interest for the six futures contracts considered. *t*-statistics computed with the Newey-West consistent estimators are reported between brackets. The data period goes from January 2000 to August 2020.

	Panel A. Convenience yield					
Time to delivery	a	SD	$UWD \times 10^5$	$DUK \times 10^4$	$OI \times 10^4$	R^2 (%)
1 month	9.53 [4.91]	0.58 [1.50]	0.13 [1.43]	−0.53 [-1.71]	−0.52 [-6.05]	26.92
2 months	17.84 [5.81]	0.97 [1.65]	0.29 [2.22]	−1.24 [-2.37]	−1.01 [-7.40]	33.36
3 months	26.45 [6.24]	1.37 [1.67]	0.47 [2.73]	−2.14 [-2.82]	−1.53 [-8.16]	36.74
4 months	35.68 [6.39]	1.81 [1.67]	0.65 [3.08]	−3.04 [-3.08]	−2.08 [-8.62]	38.93
5 months	55.22 [6.65]	2.71 [1.65]	1.02 [3.51]	−3.88 [-2.75]	−3.17 [-9.08]	40.28
6 months	53.72 [6.30]	2.81 [1.65]	1.04 [3.54]	−4.25 [-3.03]	−3.13 [-8.79]	40.17

	Panel B. Rollover convenience yield					
Time to delivery	a	SD	$UWD \times 10^5$	$DUK \times 10^4$	$OI \times 10^4$	R^2 (%)
2 months	18.26 [9.17]	0.67 [2.27]	0.38 [3.91]	−0.67 [-1.44]	−1.01 [-9.92]	39.38
3 months	26.84 [9.96]	0.90 [2.30]	0.48 [3.24]	−1.08 [-1.67]	−1.54 [-10.53]	40.86
4 months	38.42 [9.89]	1.12 [1.99]	0.58 [2.45]	−0.97 [-1.11]	−2.11 [-10.99]	42.36
5 months	59.76 [10.01]	1.74 [1.87]	0.79 [2.42]	−0.97 [-0.79]	−3.24 [-11.56]	45.19
6 months	59.87 [10.54]	1.63 [1.82]	0.72 [2.27]	−0.50 [-0.41]	−3.23 [-11.97]	44.29

	Panel C. Term risk-premium					
Time to delivery	a	SD	$UWD \times 10^7$	$DUK \times 10^5$	$OI \times 10^7$	R^2 (%)
2 months	−0.42 [0.25]	0.30 [-0.82]	−8.37 [0.91]	−0.57 [1.74]	0.75 [-0.01]	5.89
3 months	−1.38 [0.57]	0.47 [-0.87]	−0.80 [0.07]	−1.05 [2.47]	9.54 [-0.08]	7.05
4 months	−2.74 [0.88]	0.69 [-0.93]	9.82 [-0.66]	−2.07 [3.59]	2.91 [-0.19]	9.94
5 months	−4.55 [1.16]	0.97 [-1.05]	23.03 [-1.17]	−29.18 [3.97]	6.76 [-0.36]	12.55
6 months	−6.15 [1.22]	1.18 [-0.95]	31.40 [-1.50]	−37.51 [4.04]	1.01 [-0.43]	11.45

The results for the model in Equation (5) are reported in Table 3, Panel A. The explicative power for 1 to 6-month increases from 26.92 to 40.17 per cent for the convenience yield. Volatility, unexpected demand shocks in winter with storage in tight conditions, reductions in inventories, as well as low open interest, produce an increase in the convenience yield. Panel B in Table 2 reports the results for Equation (5) applied to the rollover convenience yield defined in Equation (3). It can be observed that the explicative power of the model varies between 39.38 and 44.29 per cent as the maturity increases from 2 to 6 months. It is important to highlight that monthly variations in the inventories do not have a significant influence in most cases on the rollover convenience yield. Volatility, demand shocks in winter with tight inventory conditions and low levels of trading activity measured with the open interest can partially explain the convenience yield accrued in the front contract. Estimated results of Equation (5) for the term risk-premium defined in Equation (4) are reported in Table 2, Panel C. The term risk-premium results highlight that main feature differentiating conventional and rollover convenience yield response in Equation (5) is their sensibility to inventory changes. Variations in inventories affect expectations about future values of the stored commodity, but the influence on current value or the value for the nearest maturity is small to non-existent – unless produced in tight conditions.

4.2. Relative basis should vary one-for-one with interest rate

The theory of storage states that the difference between futures and spot prices or basis should be explained in terms of interest forgone and the cost of storing the commodity and a convenience yield on inventory. Fama and French (1987) tested one implication of the above relationship: 'controlling for variation in the marginal storage cost and the marginal convenience yield, the *T-t* period basis for any stored commodity should vary one-for-one with the *T-t* period interest rate'. Their results for metals reflect this implication. For agricultural commodities, the evidence was weak. In these cases, basis variation must be explained primarily in terms of economic conditions that generate variation in storage costs and convenience yield. In the specific case of natural gas, Modjatahedi and Movassagh (2005) proposed testing the cost of carry relationship by approximating the 'net' convenience yield (cost of storing minus the convenience yield) with inventories. Consistent with the literature, they expect that when inventory is low, warehousing costs are low and convenience yield high. In contrast, when inventories are high, warehousing costs increase and convenience yield decreases. Therefore, a positive relationship between basis and inventories is expected. Following Modjatahedi and Movassagh (2005) we have estimated the following regression

$$Basis(t-j,t) = a + bUK(t-j) + c\left(LIBOR(t-j)\times\frac{j}{12}\right) + \varepsilon(t-j,t) \qquad [6]$$

for $j = 1, 2, 3, 4, 5$ and 6 months to delivery. $Basis(t-j,t) = (F(t-j,t) - S(t-j))/S(t-j)$, UK refers to natural gas reservoir levels in the United Kingdom, and $LIBOR(t-j)$ is the 3-month LIBOR average rate in the month $t-j$, and $\varepsilon(t-j,t)$ is the error term. If the theory of storage is a valid theory for pricing natural gas futures, then $b > 0$ and $c = 1$ and $a = 0$. Estimation results are reported in Table 4. We obtain partial evidence for the theory of storage. Evidence for the theory of storage is obtained for inventory coefficients as they are all positive and have high *t*-statistic values. Nevertheless, we observe considerable evidence that runs counter to the theory of storage. Firstly, interest rate coefficients are very low and only significantly different to zero for the 6-month maturity. Secondly, the intercepts are significantly different to zero with the 6-month maturity exception. Finally, the determination coefficients are quite low. Therefore, the theory of storage is not a complete model of the basis determination in the natural gas market.

4.3. Samuelson hypothesis

The Samuelson effect states that forward price volatility will decrease as the time to maturity of futures contract increases. For storable commodities, it is generally agreed that inventory levels have a strong impact with marginal convenience yield declining as a function of time (Cartea et al., 2015). Therefore, evidence for the Samuelson effect in storable commodities implies indirect evidence of the theory of storage. Following Duong and Kalev (2008) we tested the Samuelson hypothesis using the non-parametric test developed by Jonckheere (1954) and Terpstra (1952). The JT test examines the null hypothesis that all futures maturity volatilities are equal, against the alternative hypothesis that higher volatility is observed in futures with closer maturities. That is,

Table 4

Regression of basis on inventories and interest rates according to the cost of carry This table reports the estimation results of the following regression, $Basis(t-j,t) = a + bUK(t-j) + c\left(LIBOR(t-j)\times\frac{j}{12}\right) + \varepsilon(t-j,t)$. for $j = 1, 2, 3, 4, 5$ and 6 months to delivery. $Basis(t-j,t) = (F(t-j,t) - S(t-j))/S(t-j)$, UK refers to the natural gas reservoirs levels in the United Kingdom and $LIBOR(t-j)$ is the 3-month LIBOR average rate in the month $t-j$. The *t*-statistics computed with the Newey-West consistent estimators are reported between brackets. The data period goes from January 2001 to August 2020.

Time to delivery	a	$UK \times 10^6$	$LIBOR$	R^2 (%)
1 month	−0.06 [-3.00]	0.65 [3.30]	0.06 [1.00]	4.83
2 months	−0.14 [-4.54]	1.70 [5.83]	0.07 [1.61]	12.89
3 months	−0.19 [-4.39]	2.55 [6.15]	0.06 [1.34]	14.20
4 months	−0.17 [-3.50]	2.79 [5.82]	0.06 [1.35]	12.14
5 months	−0.10 [-1.82]	2.37 [4.53]	0.05 [1.59]	8.34
6 months	0.01 [0.14]	1.50 [2.60]	0.06 [1.96]	4.78

$$\begin{aligned} H_0 &: \sigma_1 = \sigma_2 = \sigma_3 = \sigma_4 = \sigma_5 = \sigma_6 \\ H_1 &: \sigma_1 \geq \sigma_2 \geq \sigma_3 \geq \sigma_4 \geq \sigma_5 \geq \sigma_6 \end{aligned} \qquad [7]$$

where σ_j is the median of the monthly standard deviation of the log-futures price returns maturing in $j = 1$, 2, 3, 4, 5 and 6 months. Volatilities are computed each month using daily prices and these are the input of this test. The JT test is carried out by comparing the observations for each month's individual volatility of each maturity with the remaining maturities for that month. That is, for each individual observation (monthly volatility) of $j = 1$ month to maturity volatility time series, we pair this observation to all other observations in the $j = 2$ months to maturity volatility time series. For each pair, in which $\sigma_1 > \sigma_2$, we record the value of 1 (zero otherwise). If there is a tie, a value of 0.5 is recorded. We sum all these recorded values to obtain U_{12}. In the same way, we obtain U_{13}, U_{14}, U_{15}, U_{16}. Adding all the individual U_{ij} for $i < j$, gives the test statistics J. For a large sample size, the JT test statistics, $Z = \frac{J - [(N^2 - \sum_{i=1}^{6} n_i^2)/4]}{\sqrt{[N^2(2N+3) - \sum_{i=1}^{6} n_i^2(2n_i+3)+3]/72}}$ is approximately normally distributed with a zero mean and a variance equal to one. Here N is the total number of observations and n_i is the number of observations of the i th individual time series. The value of the JT test statistic is 66.23 with a p-value of 0.00. Therefore, we reject the null hypothesis of equal volatility between futures with maturities one to six against the alternative that volatility is higher for shorter than for larger maturities, for any pair of maturities, and for the whole set of maturities. Therefore, we obtain indirect evidence of the theory of storage in the UK natural gas futures contracts.

4.4. *Negative relationship between price volatility and inventories*

Further to the basic result of Pindyck (2001) about the inverse relationship between volatility and inventory levels, Geman and Ohana (2009) and Suenaga et al. (2008) obtain that this relationship is stronger in periods of scarcity. We have tried to measure this relationship using inventory levels, detrended volatility with detrended inventory levels, and measures of demand shocks during winter periods. We have only obtained some significant results when monthly volatility and monthly inventory changes are related. Therefore, the following linear regression is estimated

$$\sigma_j(t) = a + bDUK(t) + \varepsilon(t) \qquad [8]$$

for $j = 1, \ldots, 6$. $\sigma_j(t)$ is the volatility of the log-returns of the futures contract maturing in j months and $DUK(t)$ the inventory changes. As can be seen in Table 5, the relationship between these two variables is negative, but only some significant results are obtained for the first and second futures contract near to maturity. From the results in Table 5, we can conclude that inventory influence on futures volatility is limited to the two closest maturities.

4.5. *Convenience yield term structure*

Correlation between futures returns for different maturities steadily decreases from about 0.90 to 0.10. Nevertheless, all convenience yield proxy return correlations have values between 0.88 and 0.99. We obtain very similar results working with the seasons in these time series. Therefore, we can say that convenience yield returns are highly correlated across all maturities, but futures returns are not, the correlation decreases far more quickly. From this correlation analysis, we can conclude that the convenience yield term structure (see Alquist et al., 2014) moves linearly in the same direction. In Fig. 4 the mean average values for the term structure of the convenience yield are drawn. We observe an increasing average term structure with steeper slopes in winter than in summer. It is quite clear that the present level of inventories determines the slope of the term structure with an inverse relationship.

The convenience yield is a forward-looking variable that contains information about future demands and has been shown to be inversely related to the inventory level of the commodity (Omura and West, 2014). An upward slope of the term structure indicates that higher value is assigned to future inventories than today's inventories, indicating that inventory is expected to be scarcer in the future. Therefore, it is interesting to check how the convenience yield spread between different futures maturities responds to variations in the inventories. Further to inventories, trading activity in futures markets might affect the slope of the convenience yield term structure. In Fig. 5 we observe that the open interest has a seasonal pattern. Reservoirs are replenished in summer to meet winter demand. This fact has its effects on futures markets as activity in summer months is higher than in winter months in order to hedge this

Table 5

Volatility and inventory relationship; This table reports the linear regression results of $\sigma_j(t) = a + bDUK(t) + \varepsilon(t)$ for $j = 1, \ldots, 6$. $\sigma_j(t)$ is the volatility of the log-returns of the futures contract maturing in j months and $DUK(t)$ the inventory changes. Where the t-statistics computed with the Newey-West consistent estimators are reported between brackets. The data period goes from January 2001 to August 2020.

Time to delivery	a	$DUK \times 10^8$	R^2 (%)
1 month	0.02 [25.50]	−0.12 [-2.35]	3.58
2 months	0.02 [25.74]	−9.31 [-2.14]	2.93
3 months	0.02 [26.09]	−4.73 [-1.61]	1.00
4 months	0.02 [26.68]	−3.03 [-1.08]	0.50
5 months	0.02 [20.76]	−1.26 [-0.40]	0.60
6 months	0.01 [28.70]	−3.96 [-1.47]	1.23

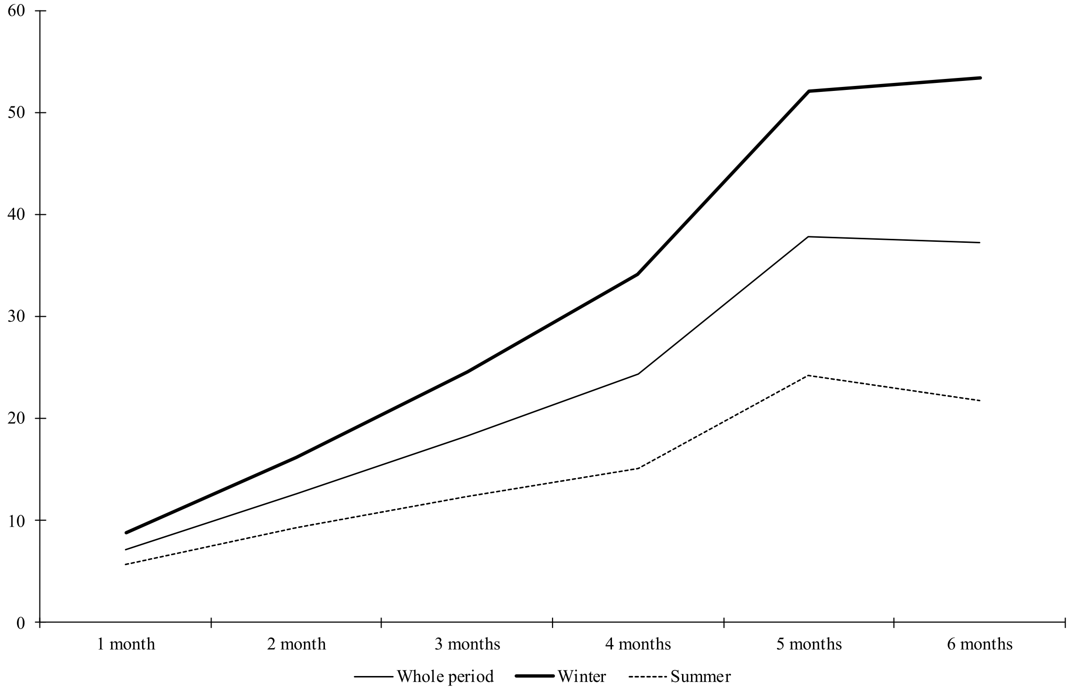

Fig. 4. Convenience yield average term structure (pence/therm).

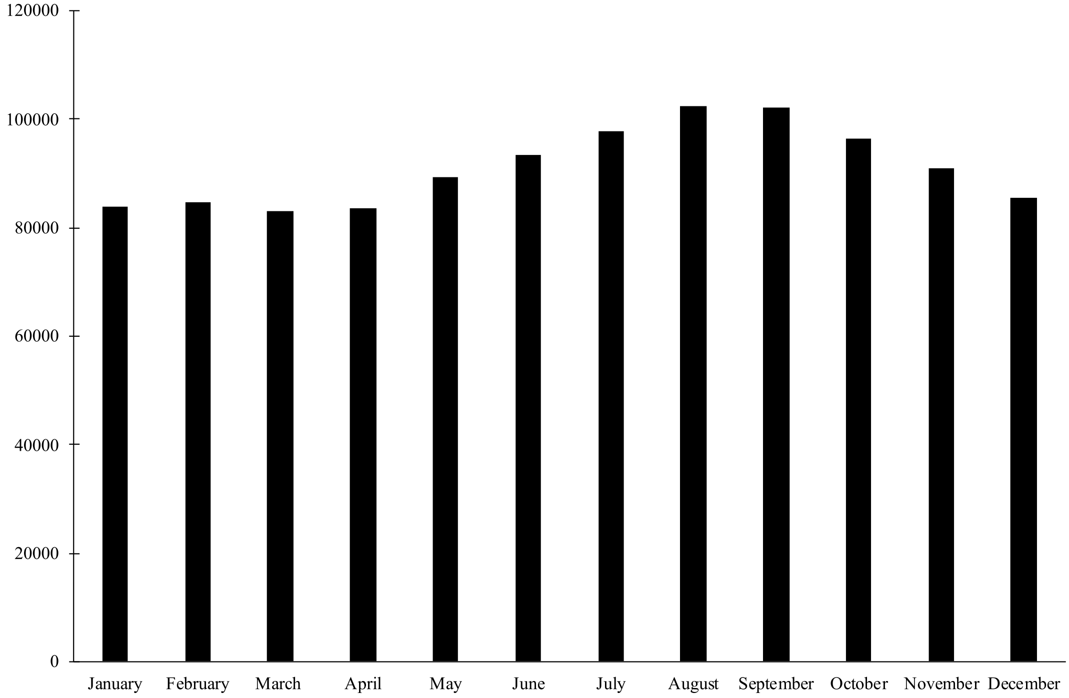

Fig. 5. Average monthly of the sum of the open interest for the six futures contracts near to maturity (number of contracts).

temporal trade across seasons. We have carried out the following linear regressions

$$CY(t-j,t)-CY(t-1,t)=a+bDUK(t-j)+OI(t-j)+\varepsilon(t-j,t) \qquad [9]$$

For $j=2,3,4,5,6$. The determination coefficient of this relationship is about 30 per cent for any convenience yield spread (as shown in Table 6). Therefore, it can be said that reduction in inventory levels and low levels of open interest steepen the slope of the term structure of the convenience yield.

5. Conclusions

The study of the convenience yield is a key factor for many companies and regulators. For example, the substitution of natural gas storage for liquefied natural gas imports will largely depend on the benefits of having readily accessible natural gas, that is, the convenience yield value. For regulators, this value is essential for planning storage facilities; and for energy traders, the switch between importing LNG or storage gas may depend on the present and expected value of the convenience yield. Producers will also consider the slope of the term structure of the convenience yield and can adapt production by looking at the expected level of inventories in the future as reflected in the term structure of the convenience yield.

The theory of storage has been scarcely tested in European natural gas markets. This study updates and completes these tests with novel concepts and analytical tools. First, this study incorporates the novel concept of rollover convenience yield or accrued convenience yield in the front contract. Second, the difference between the conventional convenience yield and accrued convenience yield in the front contracts enables us to obtain a term risk-premium. We show this term risk-premium to be an indicator of the future scarcity or excess of inventory of the commodity. Third, a convenience yield term structure is analysed for the first time in the British natural gas market, and this throws light on how convenience yield responds to reservoir level changes and trading activity in the futures markets. Finally, we show that futures markets activity measured with open interest have a seasonal behaviour inversely related with the seasonal pattern of the term risk-premium and the slope of the term structure. As reservoirs are replenished in the summer season to satisfy peak demand in winter season, so the owner of the gas uses futures markets to manage the uncertainty of the commodity in the winter, where price volatility shows its highest values.

Looking carefully to the conventional convenience yield and the rollover convenience yield we found that both measures reveal a seasonal pattern: being higher (lower) in winter (summer) when inventories take their lowest (highest) values. When the difference between both measures is analysed, we observe that the convenience yield is above the rollover convenience yield in winter and below in summer. This new result indicates that natural gas futures maturing in winter (summer) months incorporate a higher (lower) value to the expected inventories to avoid scarcity (excess of inventory) in that season. That is, a significant and positive (negative) term risk-premium in the convenience yield term structure is found in the winter (summer) season.

The first implication of the theory of storage we have studied is the seasonal behaviour of the convenience yield. Under this theory, seasonality in inventories generates a seasonal pattern in the convenience yield. But in this market, there are other variables with a seasonal pattern that spread their seasonality over natural gas prices (spot and futures). Specifically, the volatility of spot prices is higher in winter than in summer because the supply of natural gas is tight in that season and so price fluctuations are higher. Demand for natural gas exhibits a clear seasonal fluctuation: being higher in winter because of its use for heating. Liquidity in natural gas futures markets in the UK also has a seasonal pattern, being higher in summer than winter because in summer months many strategies are employed in the futures markets to hedge natural gas price risk for the winter months. All these variables together explain between 26 and 40 percent of the convenience yield across time for the six futures maturities considered. Therefore, we obtain strong evidence for the theory of storage in this first implication test.

A second implication of the theory of storage is tested following Modjatahedi and Movassagh (2005) who tested whether the basis can be fully explained with the interest rate and inventories used as a proxy of the 'net' convenience yield. We found weak evidence for the theory of storage for this implication as inventory coefficients have high *t*-statistics values, but interest rates are not a significant explicative variable. Therefore, the theory of storage is not a complete model of the basis determination in the natural gas market.

The Samuelson hypothesis sustains the volatility of futures price increases as the futures contract comes close to maturity. We have tested this hypothesis and we cannot reject it. In this way, this is indirect evidence of the theory of storage as shown in Cartea et al. (2015), namely, that inventory shocks impact on declines in the convenience yield as a function of time to maturity. Continuing with the volatility of futures prices, we have tested if these volatilities are sensitive to some variable indicating commodity scarcity. We have obtained weak evidence for this relationship, with some significant effect only in the futures contracts nearest and second nearest to maturity.

Finally, we have constructed a term structure for the convenience yield to test its response to changes in inventories and trading activity in the futures markets measured with open interest. We find that reductions in inventory levels and low levels of open interest

Table 6

Regression of convenience yield spread on the inventory changes and open interest This table reports the estimation results of the following regressions $CY(t-j,t) - CY(t-1,t) = a + bDUK(t-j) + OI(t-j) + \varepsilon(t-j,t)$ for $j = 2, 3, 4, 5$ and 6 months to delivery. $CY(t-j,t)$, $DUK(t-j)$ variables are defined in previous tables and $OI(t-j)$ refers to the sum of the average open interest across the six futures contracts considered. *t*-statistics computed with the Newey-West consistent estimators are reported between brackets. The data period goes from January 2001 to August 2020.

	Panel A. Convenience yield			
Spread	*a*	$DUK \times 10^4$	$OI \times 10^4$	R^2 (%)
6 months - 1 month	56.07 [11.67]	−4.77 [-3.70]	−2.87 [-9.80]	31.72
5 months - 1 month	57.07 [12.18]	−4.36 [-3.37]	−2.91 [-10.22]	32.53
4 months - 1 month	32.73 [11.54]	−3.09 [-3.87]	−1.71 [-9.92]	33.05
3 months - 1 month	21.17 [11.16]	−1.99 [-3.69]	−1.11 [-9.58]	31.64
2 months - 1 month	10.37 [10.82]	−0.90 [-3.34]	−0.54 [-9.05]	29.35

steepen the slope of the term structure of the convenience yield with an explicative power of about 30 per cent. These results indicate that inventory is expected to be scarcer in the future when current inventory levels decrease, and current open interest assumes low values. As was explained in Section 4, the highest values of open interest occur in the summer when strategies in futures markets are initiated to manage the price risk of natural gas in the winter. All in all, we obtain new evidence for the theory of storage as a pricing framework in this market.

Author statement

Hipòlit Torró: conceptualization, methodology, software and writing original draft. Dr. Beatriz Martínez: data curation and data description.

Declaration of competing interest

Financial support from the Spanish Ministry of Science and Innovation and ERDF is gratefully acknowledged (Grant PGC 2018-093645-B-100 funded by MCIN/AEI/10.13039/501100011033 and by “ERDF A way of making Europe"). The general objective of this scholarship is to promote the generation of new knowledge in Spanish research institutions.

We do not have any other financial or personal relationships with other people or organizations related with the subject of this research.

Data availability

Data will be made available on request.

References

Alquist, R., Bauer, G.H., Diez de los Rios, A., 2014. What Does the Convenience Yield Curve Tell Us about the Crude Oil Market? Working Paper 2014-42. Bank of Canada.

Bessembinder, H., Lemmon, M.L., 2002. Equilibrium pricing and optimal hedging in electricity forward markets. J. Finance 57, 1347–1382.

Brennan, M.J., 1958. The supply of storage. Am. Econ. Rev. 48, 50–72.

Campbell, S.D., Diebold, F.X., 2005. Weather forecasting for weather derivatives. J. Am. Stat. Assoc. 100, 6–16.

Cartea, Á., Villaplana, P., 2008. Spot price modelling and the valuation of electricity forward contracts: the role of demand and capacity. J. Bank. Finance 32, 2502–2519.

Cartea, Á., Williams, T., 2008. UK gas markets: the market price of risk and applications to multiple supply contracts. Energy Econ. 30, 829–846.

Cartea, Á., Cheeseman, J., Jaimungal, S., 2015. How to value a gas storage facility. Chapter 19. In: Roncoroni, A., Fusai, G., Cummins, M. (Eds.), Handbook of Multi-Commodity Markets and Products. Wiley.

Duffie, D., 1989. Futures Markets. Prentice Hall, Englewood Cliffs, New Jersey.

Duong, H.N., Kalev, P.S., 2008. The Samuelson hypothesis in futures markets: an analysis using intraday data. J. Bank. Finance 32, 489–500.

Fama, E.F., French, K.R., 1987. Commodity futures prices: some evidence on forecast power, premiums and the Theory of storage. J. Bus. 60, 55–73.

Furio, D., Meneu, V., 2010. Expectations and forward risk premium in the Spanish deregulated power market. Energy Pol. 38, 784–793.

Geman, H., Ohana, S., 2009. Forward curves, scarcity and price volatility in oil and natural gas markets. Energy Econ. 21, 576–585.

Jonckheere, A.R., 1954. A distribution-free k-sample test against ordered alternatives. Biometrikq 41, 133–145.

Kaldor, N., 1939. Speculation and economic stability. Rev. Econ. Stud. 7, 1–27.

Longstaff, F.A., Wang, A.W., 2004. Electricity forward prices: a high-frequency empirical analysis. J. Finance 59, 1877–1900.

Martínez, B., Torró, H., 2015. European natural gas seasonal effects on futures hedging. Energy Econ. 50, 154–168.

Martínez, B., Torró, H., 2018. Analysis of risk premium in UK natural gas futures. Int. Rev. Econ. Finance 58, 621–636.

Modjatahedi, B., Movassagh, N., 2005. Natural-gas futures: bias, predictive performance and the theory of storage. Energy Econ. 27, 617–637.

Mu, X., 2007. Weather, storage and natural gas price dynamics: fundamentals and volatility. Energy Econ. 29, 46–63.

Omura, A., West, J., 2014. Convenience Yield and the Theory of Storage: Applying an Option-Based Approach.

Pindyck, R.S., 2001. The dynamics of commodity spot and futures markets: a primer. Energy J. 22, 1–29.

Routledge, B.R., Seppi, D.J., Spatt, C.S., 2000. Equilibrium forward curves for commodities. J. Finance 55, 1297–1338.

Schultz, E., Swieringa, J., 2013. Price discovery in European natural gas markets. Energy Pol. 61, 628–634.

Suenaga, H., Smith, A., Williams, J., 2008. Volatility dynamics of NYMEX natural gas futures prices. J. Futures Mark. 28, 438–463.

Szymanowska, M., De Roon, F., Nijman, T., Van den Goorbergh, R., 2014. An anatomy of commodity futures risk premia. J. Finance 69, 453–482.

Terpstra, T.J., 1952. The asymptotic normality and consistency of Kendall's test against trend, when ties are present in one ranking. Indagat. Math. 14, 327–333.

Volmer, T., 2011. A robust model of the convenience yield in the natural gas market. J. Futures Mark. 31, 1011–1051.

Wei, S.Z.C., Zhu, Z., 2006. Commodity convenience yield and risk premium: the case of US natural gas market. Energy Econ. 28, 523–534.

Working, H., 1949. The theory of the price of storage. Am. Econ. Rev. 39, 1254–1262.