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A Dynamic Perspective

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Abstract

According to the standard analysis of commodity prices, stockpiling is a necessary signature of speculation. This paper develops an approach suggesting that speculation may temporarily push crude oil prices above the level justified by physical-market fundamentals, without necessarily resulting in a significant increase in oil inventories. Looking beyond debate on the value of oil-demand price-elasticity, showing a demand curve makes sense only if we consider a fixed time horizon (e.g. short-run). The scenario of oil demand slowly but continuously adjusting to a price fuelled by speculation implies that price elasticity of demand is an increasing function of the time horizon considered. Short- and long-run elasticities can then be used to calibrate this function. A very low very-short-run price elasticity suggests that an exogenously-driven rise in crude oil price has a very slight impact on demand in the very short run and therefore, with supply constant, leads to a minimal increase in inventories. This interpretation differs from the traditional view, according to which storage of just a few barrels is enough to raise prices when elasticity is very low. We present several analytical and numerical illustrations (with oil-demand adjustment following Gompertz, logistic and exponential paths). The role that speculation may have played in recent movements in oil prices is also discussed.

Introduction

We put forward a simple but, as far as we know, original approach that suggests speculation may (at least temporarily) push the price of physical oil above the level justified by fundamentals, without necessarily resulting in significantly higher stocks.
Recent changes in crude oil prices are behind controversies over the role of the financial markets and speculation. Many analysts have, for example, blamed speculative positions on futures markets for triggering the rise in crude oil prices in 2008. Various economists (e.g. Krugman (2008), Smith (2009)) have objected that physical stockpiling is a necessary signature of speculation, whereas speculation has sometimes been blamed even without any increase in oil stocks. In their opinion, in the absence of any accumulation of stocks, speculative flows on futures markets cannot have any effect on physical markets.
When the speculative increase is triggered by futures markets, a traditional justification for this assumes that spot and derivatives markets are in equilibrium. Taking this financial

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viewpoint, spot and futures prices must be connected by an arbitrage-free relationship. A rise in futures prices that is speculative in origin can then be transmitted to spot prices via cash-and-carry arbitrage. This trading, which causes stockpiling, raises the spot price until the no-arbitrage equilibrium is redressed.

Another more general justification works on the assumption of economic equilibrium, stating that oil is a consumer good whose (fundamental) price is set where supply meets demand. From this perspective, a price of physical oil driven by speculation above the level corresponding to the physical-market fundamentals necessarily implies the accumulation of a stock (i.e., an increase in inventories). This economic viewpoint, which encompasses the financial one, emphasises the behaviour of demand over that of arbitragers. Put simply, instead of believing that oil stockpiling raises the oil price, it holds that a crude-oil price increase leads to a reduction in demand and therefore results in the non-consumed portion of supply being stored. In this paper, we favour this (more general) economic approach which does not require specific assumptions about the origin and destination of accumulated stocks.

Some authors have already taken the view that speculation may affect the spot price without any increase in stocks transpiring. Parsons (2009) considers the case where producers, noticing that futures prices are higher than spot prices, do not increase their production when they have the possibility of doing so. This constitutes ground storage. However, in the first half of 2008, OPEC spare capacity reached a trough, making it unlikely that they were then building up inventories under the ground. Moreover, according to Smith (2009), "non-OPEC producers responded to rising prices by pushing output further up a receding supply curve – not by shutting in reserves". Saporta *et al.* (2009) cite the possible behaviour of consumers or industrial operators who dip into their inventories to delay purchases if they feel the price increase will be temporary. The corresponding reduction in these stocks may mask speculative stockpiling. To find empirical evidence of this is difficult.

The approach we are developing is different and is based on world's oil demand slowly but steadily adjusting to an exogenously-driven change in crude oil price. Our approach leads to derive the price elasticity of demand as a continuous function of the time horizon (i.e., length of run) considered. If, as a result of speculation, the crude oil price climbs above the level corresponding to the physical-market fundamentals, global oil demand will adjust to this new price only gradually, falling a little more each day. Symmetrically, the increase in worldwide stocks – slight at first – will be a little greater each day. Consequently, if after a relatively short time the price returns to that justified by fundamentals, only a very modest increase in stocks will have been observed. In other words, stockpiling will not have been a “legible” signature of speculation. In this respect, our approach may be interpreted as an attempt to reconcile the various points of view regarding the role played by speculation.

In the first section, we describe the viewpoint of analysts who consider that positions held by investors on derivatives markets were decisive in explaining the oil-price hike in 2008. In the second section, we present the economic analysis that implies stockpiling is a necessary hallmark of speculation. In the third section, we present our approach and provide numerical illustrations. The final section concludes.

1. A possible scenario of the role played by speculation in 2007-2008

In 2006, a number of politicians and financial analysts started to attribute the rise in oil prices to speculation rather than changes in market fundamentals. The magnitude of the increase in 2008, which preceded an equally spectacular fall in prices, led to many observers adopting this stance, believing that the developments in 2008 were largely due to the positions taken by investors (pension funds, insurance companies, hedge funds, investment banks and others) on futures markets.

Most analyses that highlight the role of speculation are based on the observation that this rise in crude oil prices coincided with a general increase in commodity prices. For example, the S&P GSCI Spot index gained 85% between July 2007 and July 2008. Very basically, a common explanation is that the rise in commodity prices as a whole largely originated in the sub-prime crisis, which began in July 2007 in the United States. Investors were then expecting the dollar to depreciate and inflation to rise (involving a fall in interest rates and an injection of liquidity into the banking system). To hedge against these two risks, investors bought huge amounts of commodity futures contracts. Indeed, for a few years now there has been a negative correlation[3] between oil prices and the value of the dollar. Several explanations for this relationship have been put forward. Crude oil prices are quoted in dollars. In contrast, consumers react to prices expressed in their local currency, meaning that a depreciation of the dollar makes oil cheaper in local currency. This brings additional demand that pushes prices up. Note that this causation can work in the opposite direction: for example, a rise in oil prices widens the US trade deficit, weakening the dollar. Other possible motivations for these purchases of futures contracts have also been put forward: wish to diversify portfolios of assets whose value is only partially correlated with commodity prices (for many analysts oil has emerged as a new financial asset class), intention to speculate on Chinese economic growth, etc. These purchases result in a substantial increase in the number of open positions held by "non-commercials" on the NYMEX oil futures market. In other words, commodity futures markets benefit[4] from the transfer of liquidity away from financial assets denominated in dollars. In July 2008, the sub-prime crisis proved more serious than expected and, above all, revealed itself to be global. Investors were faced with a risk of deflation (linked to the imminent recession) and a strengthening of the dollar (owing to risk aversion among investors who, amidst a worldwide recession, withdrew to dollar-denominated assets). Furthermore, a shift in market fundamentals, linked to the recession, took place. Confronted by a complete change in inflation- and dollar-related risks, investors closed their positions en masse, leading to a fall in commodity prices (the S&P GSCI Spot lost 65% between July 2008 and January 2009) and causing the market to revert back to its new fundamentals.

According to proponents of this view, the "bubble" was mainly a reflection of rational behaviour (portfolio diversification and risk hedging) and the surge in futures prices up to mid-2008 naturally filtered through to the price of physical oil, as the majority of commercial transactions resulting in physical delivery actually depends on forward or futures prices. Note that under some theoretical assumptions - markets are in equilibrium and the interest rate is constant - prices of futures and forward contracts are the same (Schwartz (1997)). Getting oil through physical settlement of a forward contract – as this occurs in practice - then means paying this oil at a futures price. Besides, when - for instance - an airline buys futures contracts to lock in the price of the fuel it will use in the future, it will eventually have paid this fuel at a futures price (even if these futures contracts are cash-settled and physical fuel is finally bought on the spot market). This realization, which relegates spot markets to the rank of micro-markets, goes well beyond the example often cited in the literature (e.g. Fattouh

[3] Bermudez-Neubauer and Homem Cristo (2008) assess the correlation between oil prices and the USD/EUR exchange rate at -93% over the 2007-2008 period. Transactions by traders speculating on this correlation may explain why it is reflected in daily quotations. Another explanation would be that, each day, the currency policies of certain oil-producing countries notify the foreign-exchange markets of the level of the US deficit.

For further insight on the relationship between dollar's value and oil prices, see Babusiaux and Pierre (2010).

[4] Note however that every long position is mirrored by a corresponding short position. Therefore, an increase in the volume of futures contracts may be associated with any type of movement (increase or decrease) in futures prices. Nevertheless, considering that the influx of money (from financial investors) could have substantially contributed to the rise in futures prices does not seem unreasonable.

(2007)), of the national companies of Saudi Arabia, Kuwait and Iran using futures prices[5] of Brent quoted on the ICE (London) for sales to Europe. Changes in futures prices would therefore "spontaneously" reflect in the price of physical oil.

Various econometric studies have used available data to estimate the role of speculation in the crude oil futures markets. It is hard to draw any obvious conclusions from this research. For example, Büyüksahin and Harris (2009) used data from the U.S. Commodity Futures Trading Commission (CFTC). Their work finds "little evidence that hedge funds and other non-commercial (speculator) positions changes Granger-cause price changes". Their "results instead suggest that price changes do precede their position changes". In contrast, Möbert (2009) of Deutsche Bank reaches the opposite conclusion: speculation, or more specifically "speculators' dispersion in beliefs", influences both oil price and its volatility. Chevalier *et al.* (2010) provide a recent survey of these econometric studies. Lastly, it is worth noting that a study based on statistical physics and the theory of complexity (Sornette *et al.* (2009)) concludes with the existence of a speculative bubble on oil price in 2008.

2. Stockpiling: a necessary signature of speculation?

The arguments traditionally put forward as evidence that a price increase of speculative origin must lead to an increase in inventories are based on the need for a financial equilibrium (non-arbitrage relationship between spot price and futures prices) or an economic equilibrium (balance between oil supply and demand). We present both viewpoints, arguing that here the wider economic perspective seems more appropriate.

On the futures markets there is undeniably a financial equilibrium[6], characterised by an absence of arbitrage opportunities, which limits the difference between spot and futures prices to just a few dollars. From this financial perspective, a speculation-driven increase in futures prices may spread to the price of physical oil via cash-and-carry type arbitrages, which involve buying oil on the spot market and simultaneously reselling it on the futures market, storing it until the futures contract expires. In reality, this arbitrage, which leads to stockpiling, may – usually at least – play only a relatively marginal role in determining prices. In addition to the previous argument that changes in futures prices would "spontaneously" reflect in the price of physical oil, we could make an analogy with the theory of contestable markets: commercial transactions are carried out directly on the basis of a smooth forward price curve, with futures prices forming a dominant psychological reference in traders' behaviour. Put simply, nobody would think of conducting a physical transaction at a price disconnected from the futures price. By this rationale, cash-and-carry arbitrage would play only a secondary role in the determination of the forward curve (of which the spot price would just be an extremity). This argument is implicitly used by certain analysts who point the finger at speculation.

However, oil is a consumer good whose price, at economic equilibrium, is set where physical supply meets demand. As a result, and as many economists including Paul Krugman[7] (2008) have stressed, if speculation causes the price to rise above that corresponding to physical-market fundamentals, physical stockpiling must occur. In other words, world consumers are

[5] The benchmark used for their sales to Europe is the BWAVE, which is the weighted average of all price quotations that arise for a given Brent futures contract during a trading day; the weights are the shares of the relevant volume of transactions on that day. Furthermore, until 2009 Saudi Arabia has priced its US-bound barrels off the NYMEX WTI front-month contract (it has recently decided to change its pricing system by using a differential to the Argus Sour Crude Index).

[6] This equilibrium depends on the interest rate, the storage costs and the convenience yield (e.g., Schwartz (1997)).

[7] Nobel Prize for Economics 2008.

unwilling to purchase all oil produced at a price determined exogenously by speculators. As Paul Krugman highlights, if financial speculators managed – one way or another – to increase the price of petrol, this would have repercussions on the material world: "faced with higher prices, drivers would cut back on their driving; homeowners would turn down their thermostats; owners of marginal wells would put them back into production". The balance between supply and demand would thus be broken, leading to a downward readjustment of price unless someone stores the excess supply. This stock then acts as an adjustment variable, allowing the financial equilibrium (non-arbitrage relationship between spot and futures prices) and economic equilibrium (where global demand for oil meets supply).
Figure 1 illustrates such a situation: if, due to the financial equilibrium, the futures price pushes the spot price above that justified by physical-market fundamentals, a stock will accumulate (guaranteeing the economic equilibrium). The greater the price elasticity of demand (i.e. the flatter the slope of the demand curve in Figure 1), the greater the quantity of the stock. As Krugman states (2008), although the elasticity of global oil demand to crude-oil price is low in the short run, it is not zero. If we take this short-run elasticity to be around -5% (e.g. Cooper (2003), Hamilton (2009)), a speculative increase in crude oil price of around 20% would require 1% of global production to be stored.
There would also have to be a continued and not just temporary increase in inventories for the price of physical oil to remain above the level justified by market fundamentals. According to many economists, without stockpiling, speculation cannot affect physical markets even if this has been blamed repeatedly in recent years (without there necessarily being any increase in stocks).

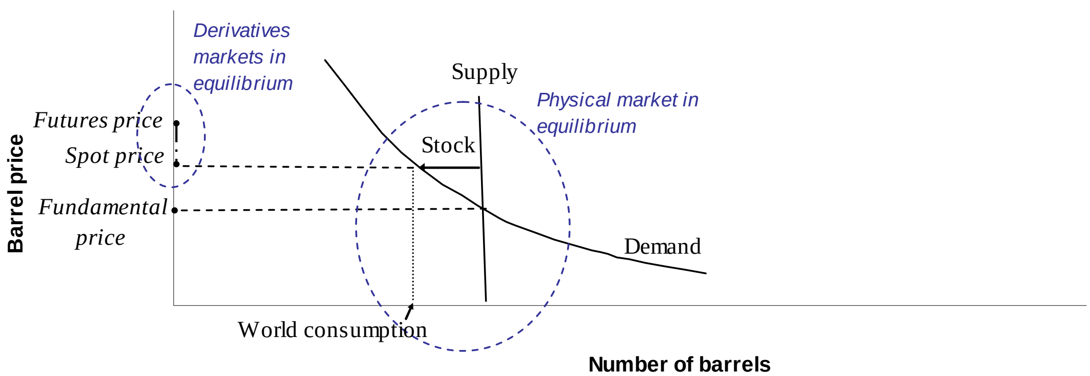

Figure 1: storage, variable of adjustment between financial and economic equilibriums

In conclusion, a parallel movement in futures and spot prices may simply reflect a change in market fundamentals. Due to the liquidity and efficiency of futures markets, the deviation in the futures price may even precede that of the spot price. In contrast, a speculative (i.e., disconnected from the fundamentals) increase in futures prices can affect the price of physical oil only via storage.

Figure 2 plots the WTI spot price as a function of OECD industry petroleum and crude oil stocks (adjusted for variations in floating stocks and expressed in days of OECD demand). This figure is similar to Pirrong's (2008) Figure 1 which shows the relationship between oil price and U.S. crude oil inventories. Both figures lead to the same observation: the historical downward-sloping price-inventory relationship[8] seems to vanish after 2003. From 2004 on, during certain periods, points go in the opposite direction, such that higher inventories may be associated with higher prices. To draw definite conclusions is however difficult. It should first be noted that data on inventories are not comprehensive and sometimes differ between agencies. Moreover, stockpiling as a signature should be assessed on a world basis, and not at the OECD scale only. In addition, until 2008, this shift in price-inventory relationships could be interpreted as the industry's response to the decrease in OPEC spare capacity (i.e., a shift of stock risk management down the crude supply chain to refiners). Krugman (2009) wrote in July 2009: "last year I was skeptical about claims that speculation was central to the price rise", "this time, however, oil inventories are bulging ... the signature of large-scale speculation is clearly visible".

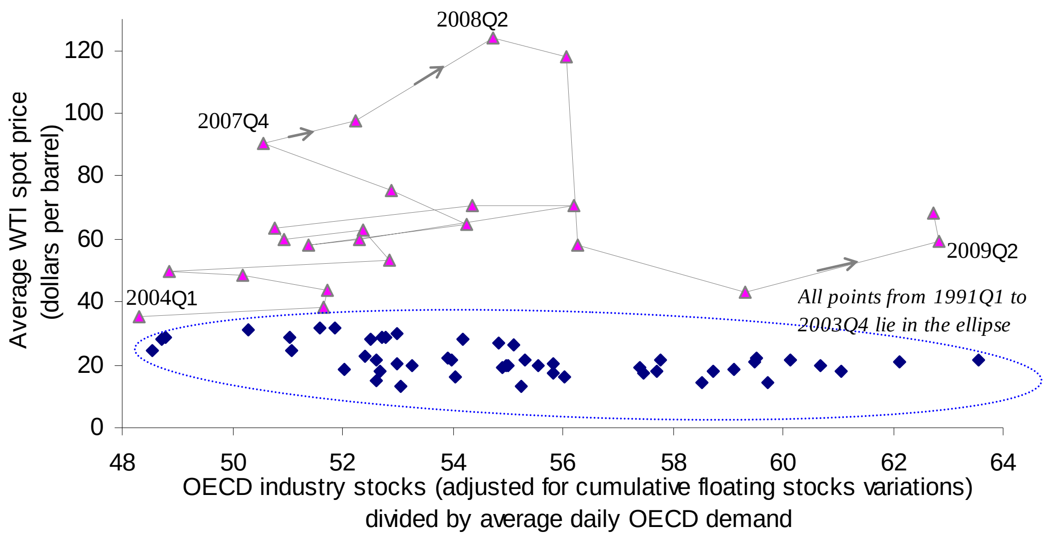

Figure 2: WTI spot price (in nominal dollars) versus OECD industry total stocks adjusted for variations in floating stocks (expressed in days of OECD demand) from 1991Q1 to 2009Q4 (quarterly data downloaded from IEA on 3/10/2010).

3. Proposed approach based on a gradual adaptation of demand

The price elasticity of demand measures the relative change in demand caused by a relative change in price. Usually, the economic literature distinguishes between short-run price elasticity, which is more directly observable, and long-run price elasticity. The short-run elasticity of oil demand to crude oil price is relatively low. Explanations include not just the difficulty in substituting petroleum products in the transport sector but also the fact that, in many countries, the price signal is hidden by subsidies or by fuel taxes that are independent of crude oil prices. In terms of absolute value, long-run elasticity is higher as it takes into account longer-term effects linked in particular to changes in vehicle fleets (replacement of old vehicles with more fuel-efficient models) as well as residential and industrial equipment.

[8] This downward-sloping price-inventory relationship is in line with the standard financial view in futures-pricing models: for instance, Schwartz (1997) writes in his footnote 4: " The positive correlation between changes in the spot price and changes in the convenience yield of the commodity is induced by the level of inventories. When inventories of the commodity decrease, the spot price should increase since the commodity is scarce ... , and vice versa when inventories increase."

As Smith (2009) highlights, "empirical estimates of price elasticity of demand for crude oil vary by place, time, and statistical techniques". Estimates and surveys drawn up by Dahl (1993), Cooper (2003) and Hamilton (2009) assess the price elasticity of demand for crude oil at between -0.2 and -0.3 in the long run and less than -0.1 in the short run. According to Smith (2009), "estimates of -0.05 (short-run) and -0.30 (long-run) are typical, with several years required to complete the adjustment to a permanent price change".

Leaving aside debate on the accurate values of these elasticities, we shall consider their interpretation in a dynamic context. To do this, let us assume that the price of physical oil, equal to *P*, is initially in line with market fundamentals, with a corresponding global oil demand equal to q_0. Let us assume that on date $t = 0$ an activity of speculative origin suddenly increases this price by ΔP, even though physical-market fundamentals remain unchanged. The price is supposed to remain indefinitely at its new speculative value $P + \Delta P$. $q(t)$ denotes global oil demand on *t*.

The long-run price elasticity, denoted ε_l, allows us to determine the level of oil demand perfectly suited to this new price. We shall call this theoretical demand "fully-adjusted demand" and refer to it as q_l. We have: $\dfrac{q_l - q_0}{q_0} \Big/ \dfrac{\Delta P}{P} = \varepsilon_l$, which gives:

$$q_l = q_0 \left(1 + \varepsilon_l \frac{\Delta p}{p}\right) \tag{1}$$

As Dargay and Gately (2009) write, "oil consumption does not respond instantaneously to changes in price and income (GDP), but instead changes slowly over time as the capital equipment adjusts". In theory, on an infinite horizon demand should therefore asymptotically tend towards fully-adjusted demand:

$$\lim_{t \to \infty} q(t) = q_l \tag{2}$$

The interpretation of the short-run price elasticity, denoted ε_s, first requires us to explain what we mean by short-run. When statistical analysis is done on real data, the short run is generally the periodicity of the data. Most econometric estimates of the price elasticity of oil demand are based on the use of annual data (e.g., Cooper (2003), Gately and Huntington (2002), IEA (2006), Dargay and Gately (2009)), the short run then being a year. Let us go back to the example of a sudden but permanent change in the oil price. Short-run elasticity then shows the change in demand observed over the first year, as an annual average. This gives us:

$$\int_0^1 q(s)\,ds = q_0 \left(1 + \varepsilon_s \frac{\Delta p}{p}\right) \tag{3}$$

For Paul Krugman, attributing a price increase to speculation in cases where there is no oil stockpiling is to deny the existence of a demand curve. But in the same way that short-run elasticity is lower than long-run elasticity, it seems plausible that very-short-run elasticity is much lower than short-run elasticity due to various rigidities: price inertia of refined products, habits, scheduled trips, etc. This is also consistent with the observation that very-short-run price volatility has little impact on oil demand.

In summary, changes in global oil demand are only partially represented by short- and long-run elasticities. In reality, demand adjusts to the new price only gradually, falling each day. As a result, in addition to (2) and (3), function *q* should theoretically meet the following two conditions:

$$q(0) = q_0 \quad (4)$$

$$\frac{dq}{dt}(t) \leq 0 \text{ for all } t \quad (5)$$

(4) reflects the fact that consumers need at least some time to respond. As we will see, this absence of an instant reaction is consistent with the view of a demand that is virtually inelastic when the time horizon under consideration is infinitesimal. (5) requires demand to be a decreasing function of time, with consumption's adjustment to the new price being seen as irreversible.

By analogy with certain diffusion processes, we can imagine an adjustment of demand following an S-shaped curve like that in figure 3. The hatched area corresponds to the satisfaction of condition (3).

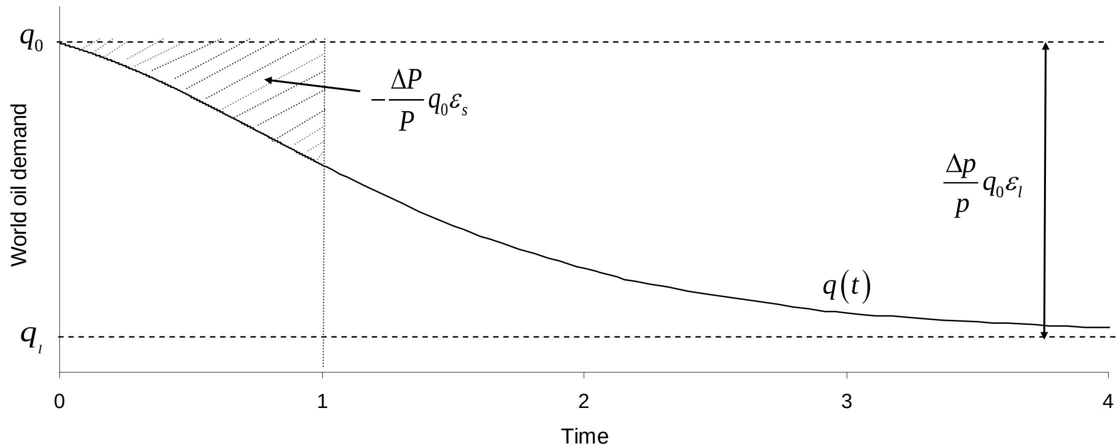

Figure 3: gradual adjustment of demand to a price that is ΔP higher than the price P corresponding to market fundamentals.

Due to the gradual reduction in demand, it is as if the elasticity observed depends on the time horizon considered, with elasticity increasing the further the horizon in question. Let us define $\varepsilon(t)$ as the elasticity given by the reduction in demand observed between dates 0 and *t*:

$$\varepsilon(t) = \frac{\int_0^t q(s)\,ds - tq_0}{tq_0} \frac{P}{\Delta p} \quad (6)$$

According to (2) and (3), we have $\lim_{t\to\infty} \varepsilon(t) = \varepsilon_l$ and $\varepsilon(1) = \varepsilon_s$ respectively. In addition, since by first-order Taylor expansion $\int_0^t q(s)\,ds \approx tq(t)$ for a small *t*, by using (4) we also have $\lim_{t\to 0} \varepsilon(t) = 0$.

Furthermore (and more importantly), (5) implies that the absolute value of elasticity ε is an increasing[9] function of the time horizon (i.e., length of run) considered: $\frac{d(-\varepsilon)}{dt}(t) \geq 0$ for all *t*.

[9] We here formalize an old line of thought: Friedman (1962) states that "in the shortest of all runs, where conditions are allowed to vary very little, one would expect the demand curve to have the least elasticity. As the

With supply (production) unchanged, that which is not consumed is, by definition, stored. The average volume of oil stocks accumulated during the period $[0,t]$ is:

$$\frac{tq_0 - \int_0^t q(s)\,ds}{t} = -\varepsilon(t)\,q_0\,\frac{\Delta P}{P} \qquad (7)$$

As a result, and with $-\varepsilon(t)$ being an increasing function of time, stockpiling will only be a visible hallmark of speculation if the latter keeps the oil price above the level justified by the physical-market fundamentals for long enough.

For the sake of illustration, Figure 4 shows the change in world oil demand calibrated according to a Gompertz curve, considering the price-elasticity of oil demand measured in annual data to be equal to -0.05 $(=\varepsilon_s)$ in the short run and -0.21 $(=\varepsilon_l)$ in the long run (see Hamilton (2009)). We assume that on date 0 the price rises to (and then remains at) a level 20% $\left(=\dfrac{\Delta P}{P}\right)$ greater than that justified by market fundamentals, with the corresponding initial demand q_0 being 31.2 billion barrels per year (i.e., 85.48 million barrels per day).

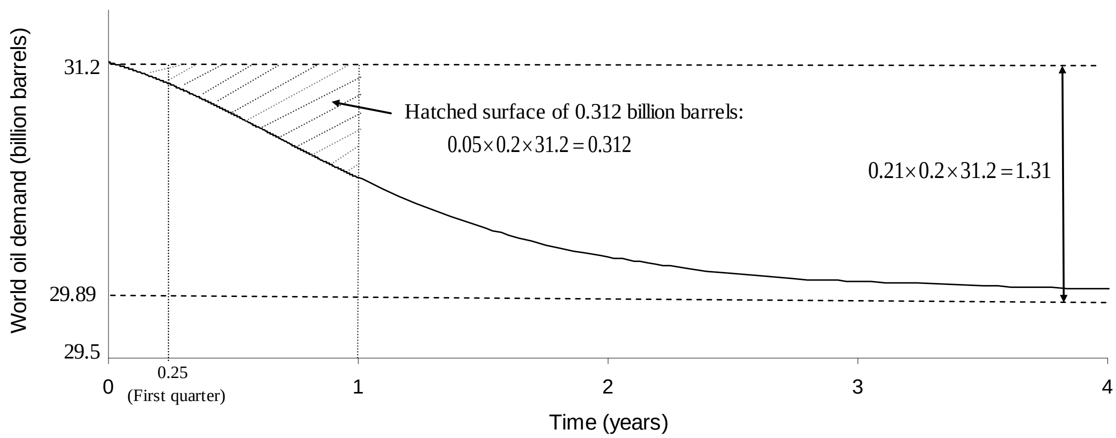

Figure 4: adjustment of demand to a price 20% higher than that justified by market fundamentals, according to a Gompertz curve.

If supply is unchanged, the difference between the new demand and initial demand must be stored. The curve in Figure 5 shows the elasticity and average daily increase in oil stocks, depending on the time horizon used. A single curve is enough to represent these two values which remain proportional according to (7). The average daily increase in stocks is just 0.17 million barrels during the first quarter, whereas it is 0.85 million barrels during the first year. Consequently, if after three months the price returns to the level corresponding to the physical-market fundamentals, only a very modest increase in stocks will have been observed.

range of conditions which are allowed to vary is widened, one would expect the elasticity of the demand curve to increase".

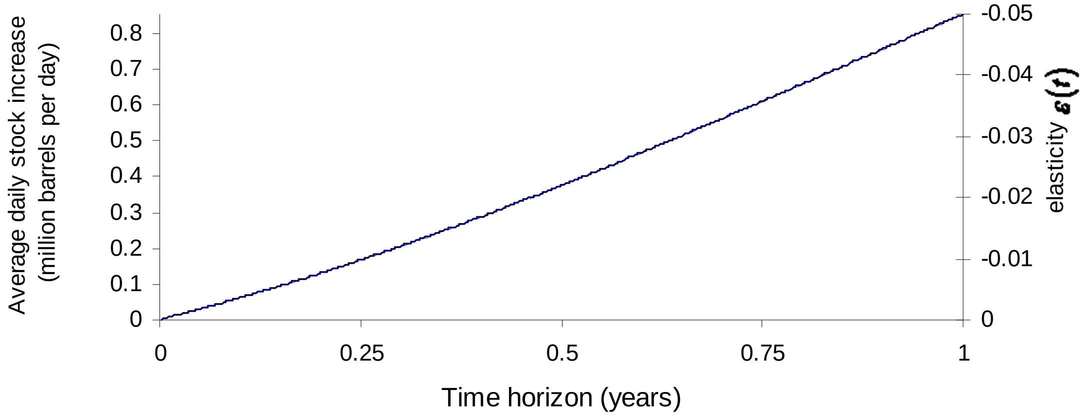

Figure 5: Average daily stock increase and corresponding elasticity, with respect to time horizon

The approach developed in this paper leads us to calculate a price-elasticity dependent on time – according to (6) – considering the reaction of demand to a change in price to be a gradual and continuous process over time. When this demand reaction follows - for instance - a logistic or exponential path, this elasticity can be determined analytically. The appendix deals with this point and provides other numerical illustrations.

In the previous analysis, we implicitly considered that the fully-adjusted demand curve, characterised by the long-run price elasticity of demand, did not move over time. Value q_l corresponding to the speculative price was therefore considered to be constant. However, the fully-adjusted demand curve can move over time, for example as a result of changes in income (GDP). From this perspective, the change in demand is a complex process with the variation in demand Δq observed over time period Δt broadly obeying the following equation:

$$\Delta q = \frac{\delta q}{\delta t}\Delta t + \frac{\delta q}{\delta q_l}\Delta q_l \tag{8}$$

Term $\frac{\delta q}{\delta t}\Delta t$ represents the effect of demand adjusting towards q_l, term $\frac{\delta q}{\delta q_l}\Delta q_l$ represents the effect of the variation in q_l. In the previous analysis, only the process by which demand evolves towards its value fully adjusted to the new price had been considered, implicitly assuming $\Delta q_l = 0$.

Illustrating a more complex situation, let us assume that in time *t* speculation suddenly pushes the crude oil price above the level justified by fundamentals, and that the price remains at this new level. In addition, let us assume that GDP growth gradually shifts the fully-adjusted demand curve to the right. As a result, during the time interval $[t, t+\Delta t]$, the oil demand starts a process of adjusting to the higher new price: $\frac{\delta q}{\delta t} \leq 0$. By shifting the fully-adjusted demand curve to the right, the increase in GDP during $[t, t+\Delta t]$ implies $\Delta q_l \geq 0$. As in theory demand can only be an increasing function of its fully-adjusted value (i.e., $\frac{\delta q}{\delta q_l} \geq 0$), terms $\frac{\delta q}{\delta t}\Delta t$ and

$\frac{\delta q}{\delta q_l}\Delta q_l$ of the right-hand side of (8) have opposite signs. Put simply, the gradual adjustment of demand to the new price is partially neutralised by GDP growth, which reduces the volume of stocks accumulated. When the price corresponding to fundamentals catches up with the actual price, the signature of speculation will ultimately have been hardly visible.
Note that this dynamic view remains formally consistent with the equilibriums in Figure 1. All the time, whatever the forces – speculation or fundamental factors - driving the physical-oil market price, the oil supply is equal to the oil demand plus the variation in inventories. Here, inventories have a passive role, in the sense that they merely serve as an adjustment variable between demand and supply.

Conclusion

As Figure 1 shows, the financial and economic equilibriums discussed in Section 2 are entirely compatible. However, we have favoured the economic approach as it does not require specific assumptions about the origin and destination of accumulated stocks. Whether or not the futures price curve necessitates arbitrage trades is ultimately not the key issue. What is important is that a speculative rise in the price of physical oil – disconnected from market fundamentals – causes an imbalance between supply and demand, which must be offset by an increase in inventories. When considering the variation in stocks to simply be the difference between supply and demand, placing the emphasis on the behaviour of demand, rather than of stocks, seems more appropriate.
The demand curve – as represented in Figure 1 – thus plays a key role in the standard economic analysis of the formation of oil prices. However, this graphic representation of a demand curve only makes sense if we consider a given time horizon (corresponding to the short run, for example). In other words, there is probably no immediately observable "static" demand curve. Indeed, demand adjusts gradually, not immediately, to changes in oil prices. We can even imagine that over an infinitesimal time period demand is totally inelastic. The scenario of oil demand gradually adjusting to a speculative price leads us to define price-elasticity as an increasing function of the time horizon considered. Short- and long-run elasticities can then be used to calibrate this function.
The traditional argument of a self-fulfilling bubble is often presented as: "when anticipating a price increase, storing a few barrels is enough to raise oil prices when short-run elasticity is small". Adopting our approach, in the very short run the argument could be: an (exogenous) rise in oil price reduces demand only slightly and therefore results in a negligible stocking.

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Appendix: analytical expression of elasticity for certain demand-reaction functions

The Gompertz curve in Figure 4 has the following equation:

$$q(t) = q_0 - (q_0 - q_l)\frac{e^{a\left(1-e^{-bt}\right)} - 1}{e^a - 1}$$

with parameters: $q_0 = 31.2$, $q_l = 29.89$, $a = 2.54$, $b = 1.436$.

A simple analytical expression of the elasticity corresponding to this reaction function of demand does not exist (the curve in Figure 5 is obtained through numerical simulation).

Let us now assume that the reaction of demand can be modelled as follows:

$$q(t) = q_0 - (q_0 - q_l)\frac{1 - e^{-rt}}{1 + ce^{-rt}} \qquad (9)$$

where *c* and *r* are given parameters.

(9), which describes an adjustment of demand that generally follows a logistic curve, satisfies (2) and (4). (9) encompasses several particular instances worthy of mention.

When $c = 0$, the adjustment of demand follows an exponential path.

When $c=1$, the adjustment of demand follows a hyperbolic tangent, with (9) then written as follows:

$$q(t)=q_0-(q_0-q_l)\tanh\left(\frac{rt}{2}\right)$$

When $c=\frac{q_l-q_0}{q_0}$, demand follows a classic logistic curve and (9) is written as follows:

$$q(t)=\frac{q_l}{1+\left(\frac{q_l-q_0}{q_0}\right)e^{-rt}}$$

We will derive the analytical expression of elasticity $\varepsilon(t)$ corresponding to a reaction from demand described by (9).

First we have:

$$\int_0^t \frac{1-e^{-rs}}{1+ce^{-rs}}ds=t+\frac{c+1}{rc}\ln\left(\frac{1+ce^{-rt}}{1+c}\right) \tag{10}$$

By combining (9) and (10) we obtain:

$$\int_0^t q(s)\,ds=tq_0-(q_0-q_l)\left(t+\frac{c+1}{rc}\ln\left(\frac{1+ce^{-rt}}{1+c}\right)\right) \tag{11}$$

According to (11), (6) gives:

$$\varepsilon(t)=\frac{P}{\Delta p}\left(\frac{q_l-q_0}{q_0}\right)\left(1+\frac{c+1}{rct}\ln\left(\frac{1+ce^{-rt}}{1+c}\right)\right) \tag{12}$$

As according to (1) we have: $\varepsilon_l=\frac{P}{\Delta p}\left(\frac{q_l-q_0}{q_0}\right)$, (12) is written as:

$$\varepsilon(t)=\left(1+\frac{c+1}{rct}\ln\left(\frac{1+ce^{-rt}}{1+c}\right)\right)\varepsilon_l \tag{13}$$

Interestingly, (13) provides an analytical expression of elasticity in function of the time horizon considered.

By making parameter c tend towards zero, we find the elasticity corresponding to an exponential adjustment of demand ($c=0$ in (9)), since for a small c we have: $\ln\left(\frac{1+ce^{-rt}}{1+c}\right)\approx c\left(e^{-rt}-1\right)$, which gives us:

$$\lim_{c\to 0}\varepsilon(t)=\left(1+\frac{e^{-rt}-1}{rt}\right)\varepsilon_l$$

Going back to the numerical illustration shown in the main section of the paper, where: $q_0=31.2, \varepsilon_s=-0.05, \varepsilon_l=-0.21, \frac{\Delta P}{P}=0.2$, let us consider the following three possible paths for the reaction of demand (calibrated to these data so as to satisfy (1) and (3)):

- an exponential adjustment $(c=0, r=0.57)$,

- a hyperbolic tangent $(c = 1, r = 0.99)$,

- a classic logistic curve $(c = -0.042, r = 0.55)$.

Figure 6 gives the three corresponding elasticity curves, determined according to (13). For the first quarter, the average daily increase in stocks is between 220,000 and 245,000 barrels only (depending on the reaction of demand considered), while in all scenarios this average daily increase amounts to 855,000 barrels over the first year.

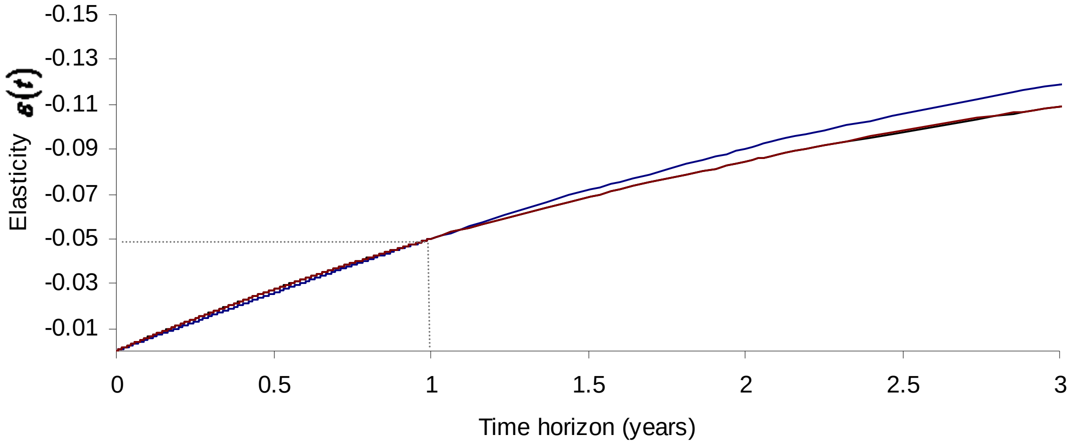

Figure 6: Elasticity curves corresponding to the reaction functions of demand defined by $(c = 0, r = 0.57)$, $(c = 1, r = 0.99)$ and $(c = -0.042, r = 0.55)$.