Speculation and Recent Volatility in the Price of Oil

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As the price of crude oil doubled from June 2007 to June 2008, suspicion grew that price was being driven higher by speculation rather than fundamental supply and demand. After having seen the price drop 70 percent from its peak, this explanation may appear more plausible than ever. This paper introduces a new methodology that uses convenience yield – imputed from futures prices – to detect the influence of speculation on the spot price of a storable commodity. The paper finds the evidence inconsistent with speculation having played a major role in the rise of price to $100 per barrel in March 2008. However, the evidence suggests that speculation did play a role in its subsequent rise to $140. Finally, the analysis finds that the collapse in price was caused by an unanticipated decline in demand rather than by speculators unloading their positions. This implies that, absent the discovery of vast new sources of energy, high oil prices will return with the recovery of the global economy.

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The past several years has been a period of unprecedented volatility for the price of oil. From January 2004 to June 2007 the price of a barrel doubled from $35 to $70 (see Figure 2, p. 14). Over the following year the price doubled again to $140. What was behind this great run-up? The suspected causes of previous episodes of volatility – embargo, production cuts by OPEC, war in the Middle East – were lacking. Instead attention focused on two explanations – demand, and later, speculation – both of which had previously received little mention in the mainstream economic discussion of oil prices.[1] While the run-up was in progress, it was generally attributed to demand, particularly from the fast-growing countries of the developing world. But as the price increase accelerated in 2007 and 2008, suspicion grew that it had come to be driven, or at least augmented, by speculation. In the summer of 2008 the US Senate conducted an investigation into the role of speculation, and considered barring speculators from the crude oil futures market. The issue was revisited recently by the CFTC's Hearing on Speculative Position Limits in Energy Futures Markets, in which the Chairman of the CFTC endorsed position limits for non-commercial traders.

The role of speculation in commodity prices has been suggested in studies by Roll (1984) and Pindyck (1993), which find that price volatility cannot be fully explained by fundamental factors. Pindyck and Rotemberg (1990) find "excess co-movement" among the prices of commodities for which the cross-price elasticities of demand and supply are close to zero, and suggest herd behavior as a possible explanation. Co-movement was a feature of the recent volatility as well; the prices of food, precious and non-precious metals, lumber, and other commodities rose roughly in tandem with the price of oil. Having witnessed the dramatic collapse that followed the peak in oil price, the role of speculation appears even more plausible, especially in light of the simultaneous collapse in the prices of other commodities. Certainly any satisfactory explanation of the rise in the price of oil must also be consistent with its fall.

The cause of the run-up in the price of oil, and its subsequent crash, remains a question of great importance. If the price was driven by fluctuations in demand, we should expect high oil prices to return with the recovery of the global economy. If speculation played a major role, perhaps we should be wary that price may be distorted by herding behavior. Of course demand growth and speculation could have both been important factors, with the latter possibly gaining

[1] Barsky and Kilian (2002, 2004), which question the role of supply disruption in previous periods of volatility in favor of demand-side explanations, are notable exceptions.

impetus from the former. There is a growing body of research which concludes that demand growth can account for the surge in price. Kilian (2009a) attributes the price increase from 2003 through 2007 to strong world economic growth. Hamilton (2009a, b) finds that the run-up can be explained by growth in demand from the developing world – China in particular – combined with a stagnant level of supply. Kilian and Hicks (2009) find that unexpectedly high economic growth, especially in the emerging economies of Asia, predict much of the increase in price through mid-2008. They also find that unexpectedly slow growth explains much of the subsequent decline. However, none of these studies test for the effect of speculation explicitly. Because of the difficulty of estimating the income and price elasticities of oil, we can only obtain a rough estimate of its "fundamental" price. As Hamilton (2009b) puts it, if price elasticity were 0.06, then price would have been predicted to rise to $142/barrel in 2008:H1; if it were 0.10, the predicted price would be $97. This leaves a large margin of error in which the effect of speculation may lie.

Several studies attempt to test for the effects of speculation explicitly. The Interim Report on Crude Oil, a preliminary study released in July 2008 by the Interagency Task Force on Commodity Markets (ITF), and a number of subsequent studies (see for example Brunetti and Buyuksahin (2009), Buyuksahin and Harris (2009)), test whether price movement is Granger-caused by the futures positions of certain classes of investors. All of these studies fail to find a link between the surge in price and speculation. However, their conclusions are not persuasive because, as we will see, speculation is transmitted to spot price through inventory, which need not correspond to outstanding futures positions. The most convincing evidence is offered by the Interim Report on Crude Oil and Kilian (2009b), which examines crude oil inventory directly. If we define the "fundamental price" to be the price at which the rate of petroleum consumption equals the rate at which it is supplied from the ground, then for any price higher than the fundamental price, supply must exceed consumption. This excess supply will build up as inventory. The ITF report finds that, within OECD countries, there was no buildup of inventory concurrent with the run-up in price.

Unfortunately this study suffers from two problems. First, we cannot observe inventory *outside* of OECD countries. Since a speculator can store oil in almost any location on earth and ship it to a refinery at some future date, this is obviously a major problem. Even for OECD countries with government-organized inventory surveys, the survey may miss some stores of oil.

These oversights are especially problematic because speculators have incentive to hide their inventory, either to prevent others from free-riding off their private information, or to prevent market participants from inferring the extent to which speculation has raised the price. A second problem is that even if we did observe total global inventory, it would be difficult to control for non-speculative motives for increasing inventory, which include anticipation of future increases in demand and disruptions to supply. Hamilton (2009a) points out that because demand for oil is so inelastic, it requires only a small increase in inventory to greatly affect the price. This would be difficult to identify from among the many other (non-speculative) reasons for adding to inventory.

The study of convenience yield – imputed from futures prices – solves these problems by offering a simple way to infer a major increase in inventory anywhere it may be. For a consumable commodity with non-trivial storage cost, such as oil, the marginal convenience yield should be inversely related to the quantity stored. If speculation had played a role in the run-up in price, we should observe a decline in convenience yield over that period. Likewise, if the sudden collapse in price was caused by speculators unloading their holdings, convenience yield should have risen as the price fell. Observing convenience yield, as opposed to observing inventory directly, also offers the benefit of controlling for non-speculative factors that can influence inventory. One major limitation of this method is that, while it can identify whether speculation has influenced the price of oil at a certain point in time, it does not tell us by how much. For that we would need an estimate of the relationship between convenience yield and inventory, as well an estimate of the elasticity of demand.

The evidence presented in this paper reveals that convenience yield did not systematically decline during the run-up until price reached about $100 per barrel. Nor did it rise during the collapse. In fact, the collapse in price was attended by some of the lowest convenience yields on record! This contradicts the hypothesis that speculation played a role in the price increase to $100, and suggests that the collapse in price was caused by an unexpected decline in demand; as oil shipments were already at sea or in the pipelines, excess supply would have caused a glut in inventory, reducing convenience yield. However, the evidence does suggest that a buildup of speculative inventory accompanied the spike in prices from $100 to $140 per barrel in the summer of 2008. In summary, speculators may have added to price volatility in 2008, but the majority of the volatility was driven by large, unanticipated shifts in demand. It is important to note that, if instead of falling demand had risen in latter 2008 (as speculators obviously predicted), speculators would have moderated the price volatility (by supplying inventory in the future) rather than augmenting it. Thus we should not conclude as a general rule that speculation increases volatility.

This paper is organized as follows. Section I develops a definition of "fundamental price," and explains how speculation might increase spot price above this level. It then reviews the nature of convenience yield in more detail, and demonstrates how it can be used to detect the effect of speculation on price. Section II applies this method to test for the effect of speculation. Section III demonstrates that convenience yield is a reliable proxy for inventory by presenting evidence of a strong inverse relationship between convenience yield and US inventory. It also extends the ITF report's study of inventory through the period of price collapse. Section IV offers some conclusions on speculation and oil, and some thoughts on the use of convenience yield in detecting the effect of speculation on the prices of other commodities.

I. A Test for the Effect of Speculation on Price

Our interest in speculation's effect on the price of oil arises from the fact that oil is a consumable good. As a consumable, there is a market clearing price at which the quantity supplied equals the quantity consumed. We can think of this as the "fundamental price." From there, we can define speculation as the belief that the fundamental price will be higher or lower in the future. If this belief causes today's price to differ from the fundamental price, then we can attribute this to speculation. It is important to note that the delineation between fundamental price and speculative effect is based on the consumable nature of oil. For investment assets there is no such delineation. It is pointless to ask *what effect does speculation have on the price of corporate equity?* The price of equity is entirely a matter of speculation; as is the case with all investment assets, if investors did not think it would have value in the future, it would have no value today. Our concern about the role of speculation on oil price is only valid if we have in mind, at least conceptually, a fundamental price.

If our concept of fundamental price is that which equates quantity supplied with quantity consumed, then for any higher price, quantity supplied must exceed quantity consumed. If speculation is to raise price above fundamental price, it follows that some supply is not consumed. We will call this quantity *inventory*. The converse is also true: if speculation builds inventory, it will increase price above the fundamental level (assuming neither supply nor demand are perfectly elastic). Speculation that price will be higher in the future provides an incentive to build inventory. Consider the strategies by which an investor who believes price will rise could profit. He could buy oil and store it for sale later, which leads directly to an increase in inventory. Alternatively, he could buy a futures contract. As Working (1949) explains, so long as the futures price exceeds the spot price plus the cost of storage, this provides an incentive for someone to store the oil on his behalf. An increase in futures prices also provides incentive for producers to store more inventory (we will explore these incentives in more detail shortly).

Not only does the effect of speculation on price create inventory, but for speculation to have a lasting effect on price, inventory must continue rising. A simple model of market equilibrium will make this clear. We will categorize the total supply of oil into three sources: 1) production from oil fields, 2) privately controlled above-ground reserves (inventory), and 3) government controlled above-ground reserves (strategic reserves). Let Q^S denote the rate at which oil is produced from oil fields, Q^I the inventory, and Q^G strategic reserves. The equilibrium spot price of oil *P* equates the rate of consumption with the rate of supply from these three sources:

$$Q^D(P) = Q^S(P) - \Delta Q^I(P) - \Delta Q^G(P) \tag{1}$$

where Q^D is the rate at which oil is consumed, and ΔQ^I and ΔQ^G are the changes per unit of time of inventory and strategic reserves, respectively. If we assume that Q^G is constant, then *P* can only be above the level at which $Q^D(P) = Q^S(P)$ so long as ΔQ^I remains positive (see the top panel of Figure 1 on p. 8). The logic is obvious: if oil is pumped from the ground at rate Q^S and consumed at rate $Q^D < Q^S$, the balance must be accumulating as inventory. If some portion of June's supply is set aside for storage, this will increase the equilibrium price in June. But unless more supply is set aside in July, price will fall as new production becomes available for consumption.

Because demand for oil is highly inelastic, it is certainly possible for inventory to accumulate in quantities sufficient to materially raise price. Kilian and Murphy (2009) estimate the one month price elasticity of demand to be -0.25. Assuming this is correct, it would require only a 5 percent reduction in quantity to raise price by 20 percent. To sustain a price increase of 20 percent for 30 days would cause inventory to increase by .05*30 = 1.5 days of supply. In the

US, inventory averages around 20 times the daily input rate of refineries, but can vary between 18 and 23.[2] Assuming the relationship between supply and inventory is similar throughout the world, this demonstrates an important fact: while storing 1.5 extra days of supply has a major effect on price, it would not stretch storage capacity beyond its limits. This illustrates Hamilton's (2009a) argument that high demand inelasticity allows speculation to influence the price.

We will define the fundamental price P^* as the equilibrium price that would prevail *in the absence of the effect of speculation* on the change in inventory, where speculation is the belief that spot price will be different in the future than it is presently. It is important to note that this definition differentiates between changes in inventory caused by speculation and changes motivated by other factors. Demand for inventory can change for a number of other reasons; producers might add to inventory in anticipation of high demand during the summer driving season or winter heating season. They might also add to inventory as a precaution against disruption to supply. Indeed, US inventory regularly varies between 18 and 23 days of supply. It has been documented that these changes in inventory demand can have a major impact on price,[3] though we will differentiate these effects from those of speculation. The precautionary motive may seem like another form of speculation; after all, inventory is being held as insurance against a future increase in price. We will develop a precise definition of precautionary, as opposed to speculative, motives for building inventory shortly. For now we can use Kilian's (2009) definition of precautionary inventory as "arising from a shift in the conditional variance, as opposed to the conditional mean, of oil shortfalls."

From our definition of the fundamental price P^*, we can define the effect of speculation as any deviation in price from P^* that is caused by the effect of speculation on inventory. This definition leaves out two other factors that determine price which one may want to ascribe to speculation. First there is the change in strategic reserves ΔQ^G. If a state becomes more concerned about the stability of future supply, it may add to its strategic reserves. While this is a forecast of the future that leads to an increase in price today, we will not include it in our definition of speculative effect because it is not motivated by monetary gain. To the extent a state does increase its reserves in the interest of profit, we can consider it a component

[2] This figure excludes the Strategic Petroleum Reserve.
[3] Kilian (2009a).

of ΔQ^I and include its effect in our definition. Second, there is the effect of speculation on the rate of supply Q^S. According to Hotelling's (1931) model of production of an exhaustible resource, if an oil producer revises upward its forecast of future prices, it will cut production today to conserve more of its in-ground reserves for sale in the future, thereby increasing the price of oil today. We will exclude this from our definition of speculation for the following reason: the infrastructure of oil extraction has a certain flow capacity; if production is set below capacity today, this does not allow production to exceed capacity in the future. To produce at a faster rate requires new investment in infrastructure. These projects require an extremely long lead time. Thus, a barrel in the ground is not a substitute for a barrel above ground for the purpose of near-term speculation.[4] Accordingly, our definition will draw a line between above- and below-ground inventory: the effect of speculation on the former is included, while its effect on the latter is not.

This suggests a simple test for the effect of speculation on price: check for an increase in inventory. As noted earlier, this approach suffers from two problems. First, our ability to observe inventory is severely limited. Second, this approach does not allow us to differentiate between the speculative and non-speculative motives for building inventory. The latter, which include preparing for seasonal shifts in demand and precaution against supply disruptions, are not easily defined or observed. It seems impractical to control for them.

Ironically, our solution to these problems is provided by the speculators themselves. By observing convenience yield, as derived from futures prices, we can infer major changes in inventory, and hence the effect of speculation on price. Convenience yield can be defined as the benefit of holding inventory, which is decreasing in the amount of inventory held. If speculation leads to a build-up of inventory, this should be reflected in a decline in convenience yield. Telser (1958) describes convenience yield as

> . . . the benefit to the firm of holding stocks, which is derived from two sources. First, the availability of stocks permits a processor or producer to maintain a given *level* of output at a lower cost than would be required without stocks. . . . Second, holding stocks permits a rate of production or sales to be *varied* at a lower cost than would be incurred if the firm attempted to purchase the stocks as they were needed.

[4] Most would agree that there will be a demand for oil for the foreseeable future, and that we should limit our consumption accordingly. But this would probably not meet with most people's definition of *speculation*.

The petroleum industry illustrates the role of convenience yield in industrial production. Even though most refineries are located near ports or pipelines to facilitate delivery of crude, they still maintain on-site stores of oil. Their motivation for doing so, in spite of the cost of storage, is convenience yield.

In this paper we use the term *convenience yield* to mean convenience yield *net* of storage cost. Define the convenience yield CY of holding inventory Q^I for a unit of time as the total convenience yield *y* net of storage cost *c*:

$$CY(Q^I; Z) = y(Q^I; Z) - c(Q^I)$$

where *Z* is a set of factors affecting the demand for inventory, such as anticipation of future demand and precautionary motives, described earlier. Marginal convenience yield (MCY) is the added convenience yield of holding one more unit of inventory:

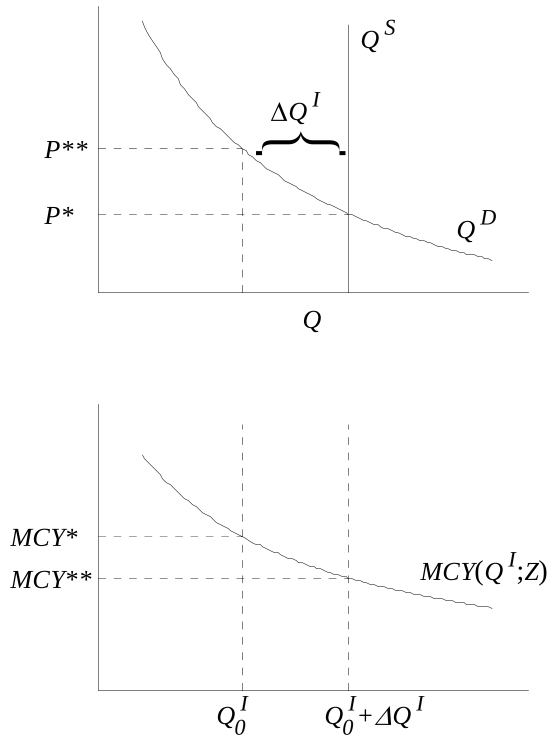
$$MCY(Q^I; Z) = y'(Q^I; Z) - c'(Q^I)$$

MCY should be a decreasing function of inventory.[5] One reason is that the marginal benefit of inventory should be decreasing: $y''(Q^I; Z) < 0$. If a refiner had only a small store of oil, the risk of running out before receiving another shipment would be considerable, and the benefit from having another barrel quite high. If the refiner had a large store of oil, the benefit of another barrel would be much less. The other reason is that marginal storage cost may be increasing ($c''(Q^I) > 0$), at least in the short-run.

The relationships among spot price, inventory, and MCY are depicted in Figure 1. The top panel shows the fundamental price *P** where $Q^D(P) = Q^S(P)$. If speculation causes inventory to increase at rate ΔQ^I per unit of time, price will rise to *P***. The bottom panel shows MCY as a function of Q^I (note that the horizontal axis in the top panel measures *Q* while in the bottom panel it measures Q^I). Let Q_0^I denote inventory level when price is *P**. After one unit of time, inventory will have risen to $Q_0^I + \Delta Q^I$, and MCY will have fallen from MCY* to MCY**. Since inventory must continue to accumulate so long as price is above *P**, MCY will continue to decline. If storage is costly, at some point the benefit of an extra barrel will be outweighed by the cost of storing it, and MCY will be negative. The MCY curve shifts in response to a change

[5] This concept is developed in Kaldor (1939) and Working (1949). Telser (1958) estimates empirical relationships for cotton and wheat, Brennan (1958) for several durable and semi-perishable farm commodities, and Pindyck (1994) for copper, lumber, and heating oil.

Figure 1



in economic factors *Z*. For instance, if demand becomes greater or more variable, or supply becomes less stable, any given amount of inventory will carry a higher convenience yield, and the curve will shift to the right.

MCY can be imputed from market prices using the familiar no-arbitrage condition, which states that the present value of the futures contract differs from the spot price by MCY:

$$P = F_\tau \exp(-r_f \tau) + X\tau \tag{2}$$

where P is the spot price, F_τ is the price of a futures contract maturing at time τ , r_f is the risk-free rate of interest, and $X\tau$ is a place holder. Whenever $Q^I > 0$,

$$MCY(Q^I; Z) = X \tag{3}$$

is an equilibrium condition for the storage of a commodity. When (3) holds, (2) states that spot price differs from discounted futures price by the marginal convenience yield obtained between the present and the maturity of the futures at time τ . This is an intuitive concept; since possession of oil confers the convenience benefit (and the cost of storage) while a futures contract does not, the futures contract trades at a discount to the spot price by the value of this benefit. If storage cost exceeds convenience benefit, then MCY is negative, and the futures contract (discounted) trades at a premium to spot price.

Equation (3) determines the equilibrium level of inventory. Consider the physical market for oil depicted in Figure 1. Suppose spot price equals $P*$. What, then, is the equilibrium level of inventory? Suppose the futures price is such that

$$P* = F_\tau \exp(-r_f \tau) + MCY * \tau \quad (4)$$

This combination of spot and futures prices provides market participants the incentive to hold Q_0^I units of inventory, because from Figure 1 this is the level of inventory at which $MCY(Q^I; Z) = MCY*$. Suppose $Q^I < Q_0^I$ so that $MCY(Q^I; Z) > MCY*$. In this case the futures price given by (4) is high enough relative to spot that it would be profitable to store oil for future delivery. As Working (1949) explains, this can be done risk-free by purchasing oil for $P*$ and selling a futures contract for F_τ. If the marginal convenience yield to be obtained by storage is greater than $MCY*$, then this yields a sure profit. Thus, oil will be stored until the marginal convenience yield equals $MCY*$, which, from Figure 1, occurs at Q_0^I. Because in equilibrium our observation of X must equal marginal convenience yield, we will refer to X as MCY when we want to emphasize this fact.

Now we can explore the mechanism by which speculation may affect spot price. First consider the effect of speculation on the futures price, which follows from the relationship between futures price and expected future spot price:

$$F_\tau = E[P_\tau \exp(-(r - r_f)\tau)] \quad (5)$$

where r is the discount rate applied to the risk of the spot price.[6] This condition states that the futures price equals the expected future spot price, discounted by a risk premium. If speculators increase their expectation of future spot price, this will increase the current futures price. This creates two distinct mechanisms by which inventory may increase. First, it incentivizes producers to store more.[7] A producer can ensure a supply of oil at a future date either by storing it or buying a forward or futures contract. When the spot price is far above the futures price, the latter is cheaper than the former. The shadow price of storing oil (X) would be high, and the producer would only choose to if the convenience yield he obtained from storing the oil was

[6] See for example Kaldor (1939).
[7] This is the motivation for Pindyck (1994).

greater than *X*. As the futures price rises, the shadow price of storage falls. If the producer's marginal convenience yield is decreasing in inventory, then he will increase inventory until it is equal to *X*. For instance, if futures price is above that in (4), then $X < MCY^*$, and it is profitable to store more than Q_0^I. If inventory increases at rate ΔQ^I then after one unit of time inventory will be $Q_0^I + \Delta Q^I$, marginal convenience yield will be MCY^{**}, and, at least temporarily, spot price will rise to P^{**}. We will refer to this as an increase in *producer inventory*.

The second mechanism leads to what we will call *speculative inventory*. If futures price is high enough relative to spot that (2) implies a negative value for *X*, there is a second motive for storage: it would be profitable for a speculator to store oil rather than buy a futures contract, provided the cost of storage is less than $|X|$. Or, if someone else can store it at lower cost, then it would pay for them to do so on behalf of the speculator. As we have already discussed, one can do this risk-free by buying oil and selling a futures contract to the speculator. At maturity, the speculator can sell the oil without having had to store it herself. As with producers, speculators will build inventory until marginal storage cost equals $|X|$. As Kaldor (1939) points out, a commodity stored for speculation carries no convenience benefit; you cannot sell it in the future if it has already been used. Since storage without convenience benefit is only rational if *X* is negative (to cover storage cost), this is a necessary condition for the holding of stock for speculation. Kaldor uses this condition to define the presence of speculative stock: "carrying costs are likely to be positive, when speculative stocks are positive, and negative when they are negative." In our empirical investigation in the following section, we will check for the condition MCY < 0 to identify speculative stocks. However, it is important to understand that speculation can potentially affect spot price through a build-up in producer inventory, without any speculative inventory.

The futures market ensures that MCY from (2) and (3) will be as low as the lowest convenience yield (or highest storage cost) pertaining to any inventory held anywhere on Earth. Consider a speculator who is deciding whether to profit from a future price increase by buying a futures contract or storing oil herself. Unless she can store oil at lower cost than $|X|$, it will be more profitable to buy the futures contract and leave the storage to someone else. Thus there will be no oil stored at greater cost than $|X|$. This means that we can rely on *X* to equal the marginal convenience yield of inventory no matter where it is held.

As mentioned previously, aside from allowing us to observe inventory build-up anywhere, another benefit of using convenience yield rather than inventory data to infer the effect of speculation on price is that convenience yield controls for the non-speculative motivations that market participants may have for changing the level of inventory. As already mentioned, producers of petroleum products might increase inventory in anticipation of higher demand for gasoline or heating oil, or because they fear disruptions to supply. All these motives to build inventory can be summed up in one: higher convenience yield. We have already demonstrated that equilibrium inventory level Q^I is determined by (2) and (3). Absent a change in P, F_τ, or r_f, the only incentive to shrink or expand inventory must come from a shift in $MCY(Q^I;Z)$, denoted as a change in some economic factors *Z*. For instance, higher demand or fears of supply disruptions could increase the marginal convenience yield of any given quantity of inventory, providing the incentive to hold more (this can be visualized as a shift right in the *MCY* curve in Figure 1).[8] The build-up in inventory will continue until (3) holds again; in other words, our observation of MCY will be left unchanged from its previous level. A lasting change in MCY can only result from a change in discounted futures price in relation to spot price, which from (2) implies a change in expected future spot price, i.e. speculation. Absent speculation, the only reason to hold inventory is convenience yield. We will use this as a formal definition of precautionary, as opposed to speculative, motives for increasing inventory, to substitute for the informal definition offered earlier: a precautionary change in the level of inventory is motivated by a shift in the MCY schedule, while a speculative change is not. Kilian (2009a) has documented the tremendous pressure that precautionary inventory demand has exerted on oil prices at various times over the past 20 years. We have also seen through our numerical example that the increase in inventory needed to cause a major short-run surge in price is small in comparison to the variations inventory normally experiences. Therefore our ability to control for precautionary inventory is essential if we are to have any hope of identifying the price effects of speculation.

Note that in contrast to previous studies which define speculators as an investor class, this approach defines speculation by its motives, regardless of who holds the position. This offers a solution to the ambiguity inherent in defining a "speculator." As Buyuksahin and Harris

[8] Alquist and Kilian (2008) demonstrate this in a general equilibrium model.

describe the problem, “commercial traders may ‘take a view’ on the price of a commodity or may not hedge in the futures market despite having an exposure to the commodity, positions that could be considered speculative.”

There are a couple of caveats that should be considered before turning to the empirical analysis of convenience yield. First, a shift in the *MCY* curve will cause an immediate change in MCY until inventory can adjust. For instance, Alquist and Kilian (2008) document that MCY spiked prior to the invasion of Iraq in 2003. They attribute this to an increased fear of supply disruption, which caused a precautionary build-up of inventory. The increase in ΔQ^I raises spot price, and hence MCY, until inventory reaches its new equilibrium level.[9] Through this adjustment mechanism, an increase in MCY can be contemporaneous with an *increase* in inventory – the opposite of what our model predicts. However, this will only hold in the short-run, until inventory reaches its new equilibrium level. For this reason we will analyze the time series of MCY at a lower frequency so that short-run movements are averaged out.

Second, while MCY controls for intentional changes in inventory, it does not control for *unintended* changes. For instance, an unexpected decline in demand can lead to a glut of inventory as shipments from abroad, or flow through a pipeline, cannot be stopped instantly. The spot price will fall relative to futures to compensate the holder of inventory for the storage cost. On the other hand, an unexpected spike in demand or disruption to supply will reduce inventory. If inventory is short, spot price will rise in relation to futures price, as having the oil now is of greater relative benefit. These shocks will follow through to our observations of MCY. However, it is easy to distinguish these effects from speculative ones, because they have opposite implications for price. Suppose we observe MCY falling over a period of time. Is this due to speculative hoarding, or an unanticipated decline in demand? The former causes an increase in spot price, while the latter will cause price to fall.

Our analysis would benefit from characterizing the “natural” behavior of MCY in the absence of speculation. Litzenberger and Rabinowitz (1995) construct a model of oil markets with demand shocks in which MCY is positive in expectation. They find the evidence to be consistent with this result: MCY was positive 94 percent of the time from February 1984 to April 1992. However, from the foregoing discussion, MCY may be negative for short periods of

[9] This is consistent with Litzenberger and Rabinowitz (1995), who find a positive correlation between MCY and the expected volatility of oil price, as implied by options prices.

time if there is an unintended build-up of inventory or if there is a shift in the *MCY* curve and inventory takes time to adjust. In their study of the convenience yield of crude oil from 1984 to 1988, Gibson and Schwartz (1990) find that MCY is mean-reverting. This is what one would expect in the absence of speculative hoarding: if inventory is high (low) because of unplanned shortages (excesses) of supply relative to demand, producers will add to (draw down) inventory until it reaches the necessary level to sustain a steady rate of production. They also find that MCY is positive on average.

To sum up the relationship between speculation and convenience yield:

1. In order for speculation to increase spot price above its fundamental level, inventory must be accumulating, either as producer inventory or speculative inventory. This will cause MCY to decline over time, at least until it reaches the long-run marginal cost of storage, where MCY < 0.
2. If there is any speculative inventory, MCY must be negative.
3. If speculation is not increasing the spot price, it is a necessary condition that MCY > 0 *over a sufficiently long period of time*.

II. Empirical Evidence

To derive MCY from (2) requires a futures price, spot price, and risk-free interest rate. We will follow the methodology of Gibson and Schwartz, who suggest that it is preferable to derive convenience yield from two different-dated futures contracts, rather than futures and spot price, because there is no true spot market for crude oil.[10] Substituting futures price for spot price in (2) yields

$$F_{t,\tau_1} = F_{t,\tau_2} \exp(-r_f(\tau_2 - \tau_1)) + MCY(\tau_2 - \tau_1) \qquad (6)$$

with MCY in place of *X*. In this case r_f and MCY are the forward rates pertaining to the period τ_1 to τ_2. We will derive MCY from the first- and second-to-mature futures contracts.[11] In

[10] Spot price is not quoted on an exchange, which makes it difficult to observe, for economists as well as market participants. Also, spot price is subject to very short-run supply and demand conditions at the location of delivery, causing it to deviate from spot price elsewhere (this is why producers hold inventory). A futures contract specifies the grade of oil, and the location and month of delivery. Because the product is standardized it can be quoted on an exchange.

[11] Trading on a contract ceases several days prior to the month of maturity; for instance, trading on the May 2009 Brent contract ceases on April 15. When trading re-opens on April 16, the traded contract with the nearest maturity is the June contract.

computing MCY it is assumed that delivery occurs on the first day of the month of maturity. The forward risk-free rate is estimated from an interpolation of the constant-maturity rates on the one- and three-month T-bills.

Figure 2 plots the monthly average of daily (annualized) MCY from August 2001 through June 2009 for the Brent futures contract, traded on NYMEX.[12] It also plots the monthly average of the daily closing price of the first-to-mature Brent contract, which we can use to approximate the spot price. The left-hand axis marks the minimum and maximum, 10th and 90th percentiles, and zero values for MCY. To verify our results, Figure 3 displays the same data for the West Texas Intermediate (WTI) contract. WTI and Brent specify different grades of oil and different point of delivery (WTI in Oklahoma, Brent in Britain), and are, respectively, the first and second most heavily traded oil futures contracts.

In figures 2 and 3 MCY clearly exhibits a mean-reverting tendency throughout the period. From the discussion in Section I, this is what we would expect in the absence of speculation. The Brent contract does exhibit a long period of generally negative and declining MCY from April 2005 through March 2007 (November 2004 to June 2007 for WTI). This may indicate a buildup of speculative inventory during this period. However, this period is not associated with a consistent increase in spot price. As Brent MCY records its lowest level of the period in October-November 2006, price reaches its lowest level of the year. When price begins to rise steadily in early 2007, MCY rises also. The simultaneous rise in price and MCY is consistent with a positive demand shock in early 2007, and inconsistent with increases in speculative inventory. From February to March 2008, as oil passes $100 per barrel, MCY increases for both contracts, to levels above their respective 90th percentile over the sample. Again, the simultaneous increase in price and MCY indicates a positive demand shock, and is inconsistent with speculation having played a role. This supports the claim that the fundamental price of oil reached at least $100 per barrel in 2008.

The final phase of the price increase is more dubious. The monthly average price of Brent rose from $103 in March to $134 in July (reaching even higher values for a short time). However, after March, MCY on Brent falls consistently, with a negative average during July, the month of the highest average spot price. WTI exhibits a similar pattern. If the price increase

[12] August 2001 is chosen as the beginning of this analysis because it is the start of trading in one month Treasuries.

Figure 2: Brent Price and Convenience Yield

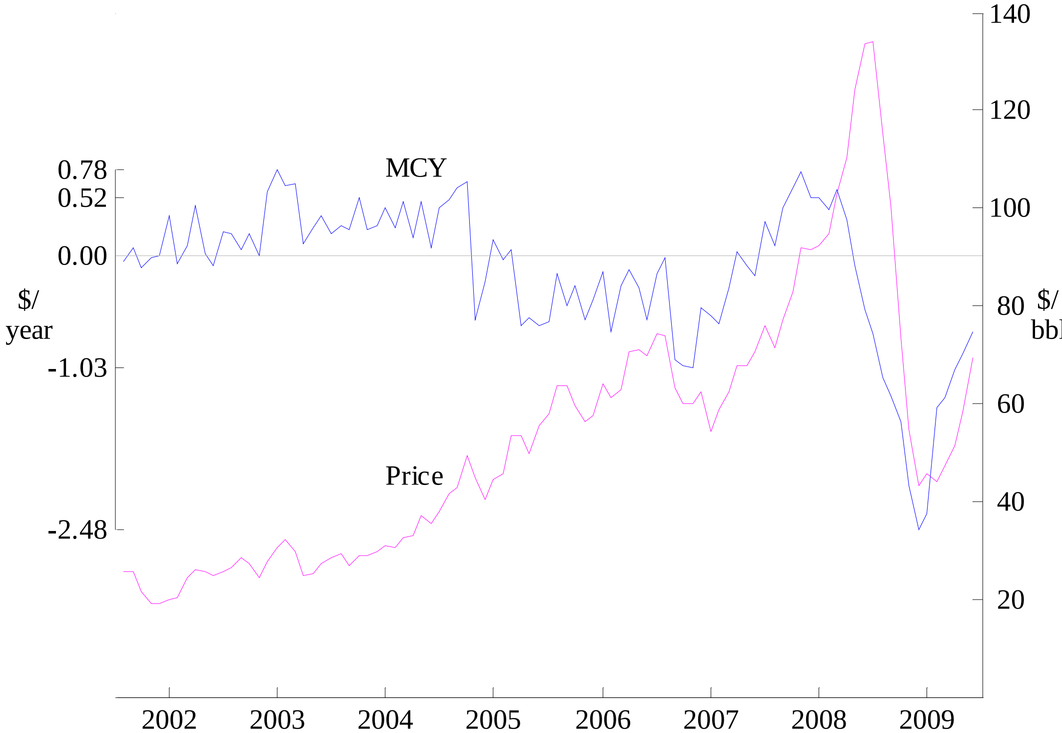
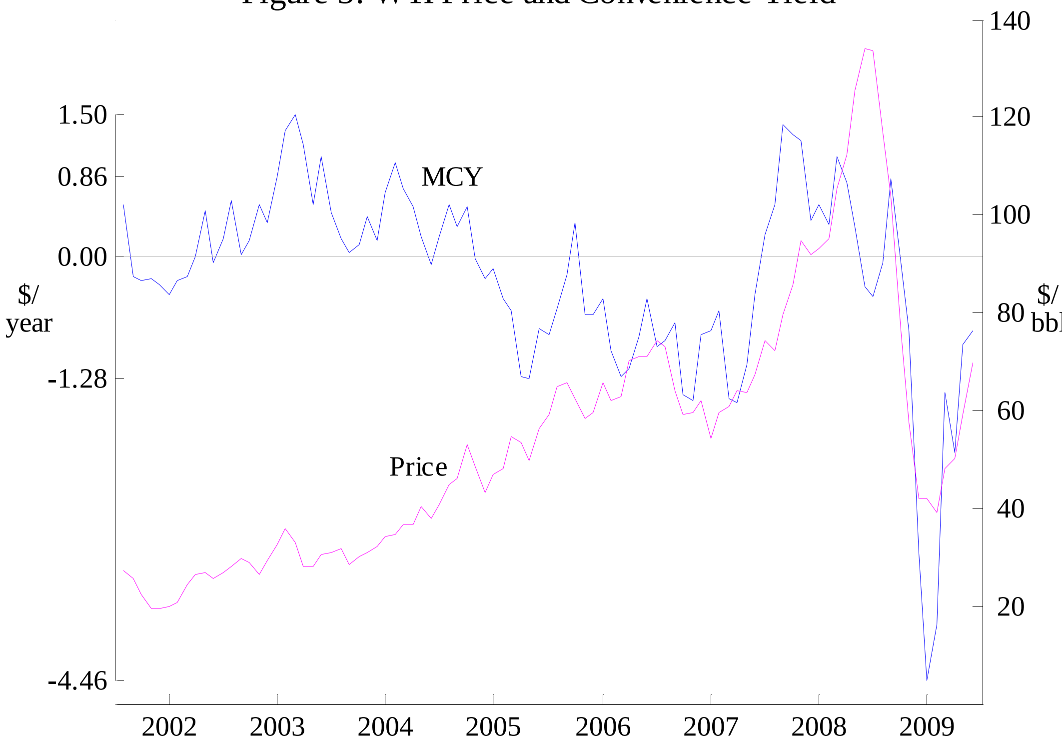


Figure 3: WTI Price and Convenience Yield



was instead due to a positive shift in demand, the magnitude and rapidity of the price increase suggests that demand growth was unanticipated. But if this were the case, MCY should have risen as refiners fulfilled the new demand out of inventory. The fact that we see the opposite suggests that the rise in demand during this brief period was at least partly that of speculators building inventory.

The crash in prices that soon followed may have been speeded by speculators unloading their inventory, but this was clearly not the dominant factor. If that were the case, falling inventory would have driven MCY back up. We find the opposite. MCY continued falling throughout the latter half of 2008, and remained below its 10^{th} percentile level from October 2008 through February 2009. For both contracts MCY hit its lowest levels of the time period we have graphed, the WTI registering the lowest average monthly MCY since the contract began trading in 1984. This implies a glut of inventory. Because price was falling, this cannot be attributed to speculative inventory buildup, but rather to an unanticipated decline in demand.

What conclusions can we make about oil price today? While price has almost doubled from its lowest level earlier this year, MCY remains negative. This is consistent with accounts in the business press that worldwide inventory levels remain high. It is difficult to attribute this to a leftover inventory glut from the drop in demand late last year. If this were the case, the price would not have risen. Instead, the coincident rise in price and negative MCY indicate that stores of oil have been set aside in expectation of higher prices in the future.

There are a few notes of caution that go along with this analysis. The power of our empirical test depends on the slope of the demand curve. It is apparent from Figure 1 that if demand is highly inelastic, a large increase in price can be achieved with only a small increase in inventory. Hamilton (2009b) suggests this may have allowed speculation to raise oil prices in 2008 without being detected by market participants (or economists). This could also defeat our use of MCY as a gauge of inventory. Unless the MCY curve is also sufficiently inelastic, a small change in inventory would go unnoticed. This would be a problem if we were trying to infer an absence of speculative inventory buildup from an absence of change in MCY. But in the foregoing analysis we have avoided such inferences. Instead we have used changes in MCY to rule out contradictory changes in inventory. For instance, we have used the increase in MCY in 2007 and early 2008 to rule out the buildup of inventory during this period. This conclusion holds as long as the *MCY* curve has a negative slope. Section III presents evidence that marginal convenience yield does indeed vary inversely with inventory.

Inventory could potentially rise without causing a drop in MCY if speculators could build more storage facilities. Clearly they have the incentive to do so, since buying futures requires paying the cost of storage. If adding to storage shifts the MCY schedule to the right, an increase in speculative stores of oil could be accommodated without any observed change in MCY. However, this seems unlikely. While speculators may build storage facilities, or make use of idle tankers, the stored oil will, at best, have zero MCY because it yields no convenience benefit, as mentioned previously. Thus the construction of storage would only modify the MCY schedule by making it elastic at some negative value. We have already identified negative MCY as a flag for potential speculative stores.

There is also concern that futures contracts do not reflect the true price of oil, and hence the true MCY, when inventory is very high. Limitations to delivery and storage capacity at contract delivery points could cause near-maturity futures contracts to trade at a discount to world market prices when inventory levels are high. Indeed, this problem depressed the price of near-term WTI contracts in early 2009, causing them to trade at a discount to Brent, even though WTI specifies a higher grade of oil.[13] Since a back-log of delivery should clear with time, the near-maturity contract may be depressed relative to longer contracts, creating an artificially low MCY. The extreme volatility in WTI MCY relative to Brent MCY following the price collapse casts doubt on its reliability. The Brent contract is supposedly less susceptible to delivery and storage limitations because its delivery point is a sea port rather than a pipeline terminal. This may explain why MCY on Brent did not fall as low as on WTI in late 2008 and early 2009. However, it has been noted that in early 2009 near-term Brent contracts traded at a discount to Persian Gulf oil, which has a lower grade than Brent.[14] This suggests that storage limitations do affect Brent, and hence MCY observed from Brent contracts may also be artificially low following the price collapse. Even so, this does not change our analysis. Observations of MCY would only be artificially low if there was a large increase in inventory, which is the inference we drew from the low values of MCY in the first place. Evidence in Section III demonstrates

[13] "Nymex Oil Loses Glow As An International Benchmark" Dow Jones Newswires 2009.
[14] Horsnell et al. 2009.

that the dramatic decline in MCY in latter 2008 was in fact accompanied by very high inventory in the US.

III. Evidence on Convenience Yield and Inventory

This section verifies our conjecture that marginal convenience yield is inversely related to inventory. It also provides evidence that inventory was not high when oil price was at its peak, and did in fact increase as the price fell. Though we do not have worldwide inventory data, inventory held within the US is compiled weekly by the US Energy Information Administration (EIA). If the costs and benefits of storing oil within the US are similar to those abroad, we should expect to find the inverse relationship between convenience yield and inventory assumed in our model. Since the convenience yield on a given quantity of inventory depends on the level of demand, we will express inventory as the ratio of inventory to the daily rate of US refinery input, also reported weekly by EIA. Figure 4 plots MCY against the inventory ratio for each week, August 2001 through June 2009 – a total of 413 weeks. To avoid endogeneity induced by the effect of US inventory glut on WTI prices, we impute MCY from the Brent contract. The axes designate the minimum, median, maximum, and 10th and 90th percentiles for inventory ratio and MCY.

The inverse relationship observed in Figure 4 is confirmed by regressing MCY on the inventory ratio (results reported in Table I). The inventory ratio explains 25 percent of the variation in MCY. Figure 4 also reveals that US inventory was not high during the week of July 3, 2008 when price hit its peak. In fact, inventory was at the low end of its typical range. This is consistent with the ITF Report, which found that inventory in the US as well as combined OECD countries were within their typical seasonal ranges in the early summer of 2008. This presents a puzzle in light of our finding that MCY had fallen to negative levels by that time. One explanation is that excess inventory was being stored outside of the OECD. The low level of MCY certainly suggests this possibility, and casts doubt on our ability to conclude from OECD inventory levels that speculation had not increased the price.

Figure 4 traces the path taken by US inventory from the peak in price of July 3, 2008 through its nadir the following February. This supports our interpretation of MCY during that period. The fact that MCY fell along with price, rather than rising, was interpreted as an indication that a drop in demand had caused price to fall and inventory to rise. Inventory certainly did rise in the US, recording some of its highest levels while MCY recorded some of its lowest and price reached levels not seen in over three years. The inventory data affirms our conclusion that the price collapse was the result of a demand shock rather than speculators selling their inventory.

Figure 4: Convenience Yield and US Inventory

Weekly, August 2001 - June 2009

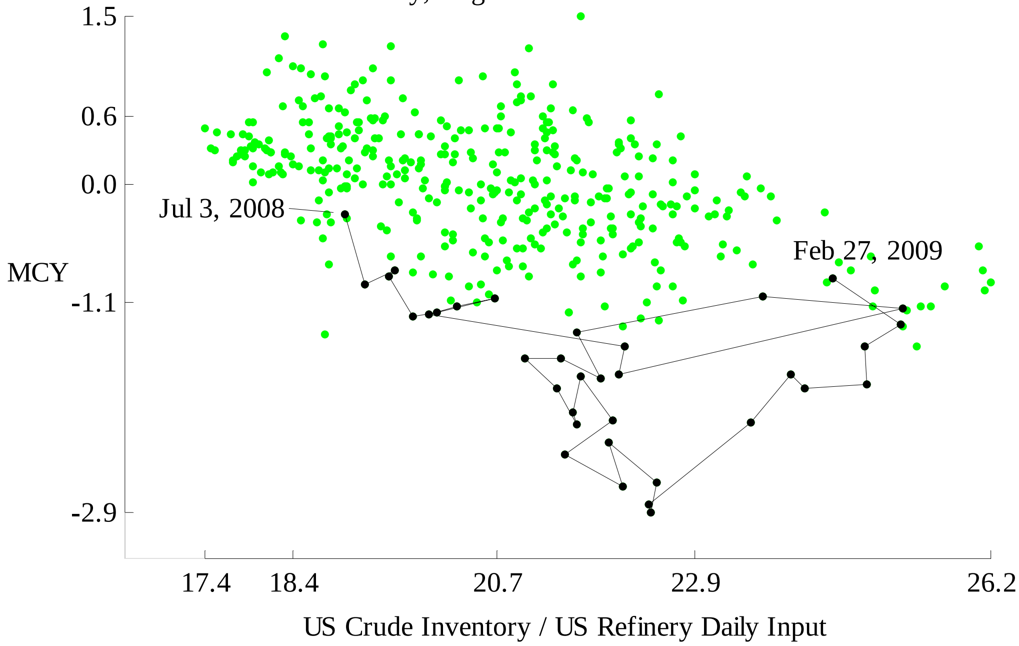


Table I

Regression Results: Convenience yield on inventory

Marginal convenience yield is regressed on inventory ratio, measured at the end of each business week. The sample runs from August 2001 through June 2009, which includes 413 weeks. Marginal convenience yield is imputed from first-to-mature and second-to-mature NYMEX Brent futures prices. The inventory ratio equals US crude oil inventory (excluding Strategic Petroleum Reserve) divided by US refinery daily input rate. P-values are reported beneath the coefficients.

Intercept	3.772
	0.000
Inventory ratio	-0.188
	0.000
R-Squared	0.253

IV. Conclusions

In this paper we have drawn a number of conclusions from the evidence on price and marginal convenience yield. Speculation did not play a role in the historic rise in oil price to $100 per barrel in early 2008, though it is likely that the building of speculative stores did contribute to the rise in price from that level to the peak price of over $140 later that year. The following collapse in price was due to a demand shock rather than the unloading of speculative positions. Finally, the recovery in price in the first half of 2009 has been accompanied by inventory held for speculation.

It is important to understand that the presence of speculative stores is not a sign of market inefficiency or investor irrationality. It is rational to store oil if the expected increase in price (as reflected in the futures price) exceeds the cost of storage. Rather than adding to the volatility of price, this should, on average, reduce it. If investors are correct that price will be higher in the future, then storing oil will moderate price, raising it while inventory is built up and lowering it when inventory is drawn down (presumably when demand is higher). Working identified this as a fundamental function of futures markets over 60 years ago. In hindsight, the market did not work this way in 2008. When demand was high in the spring and summer of that year, speculators added to inventory, thereby increasing the price further. But they turned out to be wrong. Instead of rising, demand fell later in the year, and price collapsed. Therefore, speculation may have increased the price above its fundamental level without accomplishing the offsetting moderation of price increases in the future. But we should note that the rise and fall of price in 2008 was not the outcome of speculators changing their minds, switching from accumulating inventory to dumping it on the market. The evidence demonstrates that the collapse was caused by an unanticipated decline in demand, a conclusion that is consistent with the worldwide recession. Oil speculators were not the only ones who failed to predict the recession. Stock "speculators" did as well; the price of stocks worldwide declined by the same order of magnitude as the price of oil in latter 2008. The US Department of Energy was also wrong with respect to oil prices, predicting in the summer of 2008 that prices would remain near their current levels or rise in the foreseeable future. But we should not expect investors to be wrong on average, so speculative stores should, on average, moderate prices.

It is also important to recognize that it is not economically inefficient to store oil above ground. It is a technological feature of oil production that capacity cannot be expanded quickly. This means that oil in the ground is not a substitute for oil above ground. Therefore, if demand is expected to grow in the near future, during times of excess capacity some production should be set aside in storage.[15]

Aside from oil, many other commodities – wheat, corn, soybeans, copper, nickel, natural gas – experienced a similar run-up in price followed by collapse, over roughly the same period. As with oil, the prices of these goods are widely believed to have been influenced by speculation, especially for those represented in commodities indexes, which saw heavy buying from commodity funds during the run-up in price. The analysis developed in this paper may help to inform our understanding of some of these commodities as well. Of course, the applicability of inferring inventory from convenience yield is limited to those commodities for which the MCY curve is neither too elastic nor too inelastic. In the first case, as is true of gold, storage cost is so small that there is little observable change in convenience yield regardless of how much is stored. In the second case (for example feeder cattle) inventory cannot vary separately from supply because storage is not possible. While the nature of storage in these limiting cases renders it impossible to infer changes in inventory from convenience yield, it also makes the issue of speculation's effect on price moot. Kaldor explains that for commodities with a highly elastic supply of storage, price is *entirely* a matter of speculation. If a supplier expects a certain price in the future, he would not sell it for any less today. For commodities where storage is not practical, speculation and storage cannot have any effect on price since all supply must be consumed immediately. [16]

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[15] The present production capacity of oil is in fact unknown, because many oil exporting countries keep their capacity a secret.

[16] These concepts are formalized in French (1986), which expresses the elasticity of spot price with respect to expected future price as a function of the elasticity of marginal convenience yield with respect to inventory. This relationship is tested empirically in Fama and French (1987). Working (1942) explains the implications of this relationship for futures prices.

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