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# Does the Market React Optimally to Oil Field Discoveries?

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**Abstract**

The Hotelling rule argues that the price for a non-renewable resource adjusts to the shadow value of the resource, reflecting the remaining availability of the resource. We derive the expected decline in the price of crude oil to unanticipated oil field discoveries following a standard Hotelling model and compare its predictions to the observed price adjustment. In addition, a measure of deviation from the social optimum is computed. We find that the price declines on average by 0.86% on discovery days. Furthermore, the price shows a subsequent increase two days after discovery announcements in line with the Hotelling rule. The degree of adjustment to the new level of scarcity is not found to differ significantly from the adjustment supposed to take place in the social optimum. Thus, there is evidence that the market reacts to news about scarcity as predicted by the Hotelling rule.

## 1 Introduction

With soaring prices for many non-renewable resources, one question is repeatedly being asked: Are prices of non-renewable resources optimal? The notion of optimality with respect to the behavior of non-renewable resource prices has been first described by Hotelling (1931): Under simplifying assumptions, the socially optimal price of a non-renewable resource should be increasing at a rate comparable to assets with similar risk characteristics. His result has formed the basis for the subsequently growing discipline of resource economics investigating how this result changes with alternative sets of assumptions.

While the resource economics discipline is rich in theoretical contributions on the Hotelling rule, its empirical evaluation faces many difficulties. A test on the optimal evolution of the price of a non-renewable resource encounters the reconstruction of the entire trajectory which is influenced by a magnitude of factors at the same time. Among these attempts, only few find evidence for the Hotelling rule. Most studies rather find that the dynamics of the Hotelling rule have not been a significant force governing the evolution of observed price paths of non-renewable resources (Livernois, 2008, pg. 37).

However, some factors which are important for evaluating the optimality of resource prices have not been empirically investigated, yet. One of them is the impact of reserve discoveries on the price path. Such a resource discovery leads to a sudden adjustment of the perception of scarcity. The opportunity cost of using the unit today subsequently declines and leads to a discontinuous jump in the price of the underlying. Livernois (2008) assumes that "major unanticipated discoveries would have a significant downward effect on scarcity rent and hence market prices" (pg. 29). An investigation of the price effect of discoveries promises to be worthwile not only because geologists such as Laherrere (2007) have found that discovered quantities of non-renewable resources such as crude oil actually project future supply. It is also interesting as the effect of discoveries on the price of non-renewable resources has been frequently used in resource economics textbooks (such as Perman et al. 2007) to illustrate the interrelation between scarcity and the price of the underlying.

The lack of empirical contributions on this topic is all the more surprising as an investigation of the price effect of unanticipated discoveries is an elegant way to investigate the validity of the Hotelling rule. Through a change in the user cost, unanticipated discoveries affect Hotelling's static efficiency condition. The rise in the user cost does not change as it is driven by an exogenously given rate. Thus, the dynamic efficiency condition remains unaffected. This circumstance enables a test of the Hotelling rule in which one focusses only on distinct points in time, avoiding an error-prone re-construction of the entire price path.

In order to test whether the static efficiency condition of the Hotelling rule holds, the events of reserve discoveries must satisfy two prerequisites: First, the discovery needs to be unanticipated. Only in case of an unanticipated discovery, a sudden reaction of the price should be detectable. We identify unanticipated discoveries by the reaction of stocks of oil companies to their announcement of a new discovery. Secondly, the discovery needs to be large enough. We use the Hotelling model to derive the expected decline in the price of the non-renewable resource following an oil field discovery.

The focus of our analysis is on crude oil as the recent price increases have re-freshed worries on a soon-ending of oil. In addition, discoveries of large oil fields have become rare within the last two decades, supporting fears of a soon-ending of oil. It is therefore of interest to estimate the value the market places on news of reduced scarcity.

## 2 Theoretical background & Hypotheses

The impact of a resource finding on the optimal price of a non-renewable resource can be illustrated in the standard Hotelling model. We assume a perfectly competitive market[a] where every resource owner maximizes revenues over time from resource extraction:

$$\max_{R_t} \int_0^\infty p_t R_t e^{-rt} dt \tag{1}$$

subject to the constraint

$$\int_0^\infty R_t \leq S_0. \tag{2}$$

$R_t$ is the extracted quantity, $p_t$ is the market price, $r$ is the constant interest rate and $S_0$ the size of the resource stock. Extraction costs are set to be zero. The maximization problem is solved with the current-value Hamiltonian

$$H_t(R_t, \lambda_t) = p_t R_t - \lambda_t R_t \tag{3}$$

where $\lambda_t$ is the shadow cost of resource extraction.[b] The first order conditions read

$$\frac{\partial H_t}{R_t} = p_t - \lambda_t = 0 \tag{4}$$

[a]Note that the results do not change in the case of a monopoly or an oligopoly for the assumption of an iso-elastic demand curve.

[b]It is also referred to as user cost or opportunity cost of resource extraction.

$$\Leftrightarrow p_t = \lambda_t$$

and

$$\frac{\partial H_t}{S_t} = \dot{\lambda}_t - r\lambda_t \tag{5}$$

$$\Leftrightarrow \lambda_t = \lambda_0 e^{rt}$$

Equation (4) is known as the static efficiency condition: at every point in time, the shadow price of resource extraction, $\lambda_t$, needs to be equal to the revenue gained from extraction $p_t$. Equation (5) is known as the dynamic efficiency condition: with ongoing extraction, each unit of the resource becomes more valuable. The increase in the asset value of the resource, $\frac{\dot{\lambda}_t}{\lambda_t}$, needs to be equal to the interest paid on an asset with comparable risk characteristics, $r$. The welfare maximizing solution for extracting a nonrenewable resource requires both conditions to hold at the same time, resulting in the Hotelling rule (Hotelling, 1931):

$$p_t = p_0 e^{rt} \tag{6}$$

An increase in the resource stock, $S_0$, at a later date than $t = 0$ reduces the shadow cost of resource extraction, $\lambda_t$. The welfare maximizing solution requires that the price, $p_t$, adjusts to the lower shadow cost, $\lambda_t$ in the same period of time $t$ (Equation (4)). The rate of increase of the shadow price is, however, not affected as it is given exogenously by the interest rate, $r$. Thus, the discovery of a non-renewable resource affects the static efficiency condition (Equation 4) through a change in the current price level, $p_t$, but leaves the dynamic efficiency condition unaffected. Recurring resource discoveries thus cause the well-known chain-saw pattern in resource prices (Figure 2, Dasgupta and Heal, 1979) with discontinuous jumps on the day of discoveries and a constant increasing trend between discoveries.

Assuming a functional form for the demand curve, it is possible to explicitly solve for the price level. The demand curve is assumed to be iso-elastic:

$$D_t = p_t^{-\eta} \tag{7}$$

As the welfare maximum requires total extraction of the resource stock, i.e. $\int_0^\infty D_t = S_0$, the initial price level is given as

$$p_0 = \left(\frac{1}{\eta r S_0}\right)^{\frac{1}{\eta}} \tag{8}$$

The initial price level depends negatively on the stock size. The rate of price decline is constant and given by the demand elasticity:

$$\frac{\partial p_0}{S_0}\frac{S_0}{p_0} = -\frac{1}{\eta} \tag{9}$$

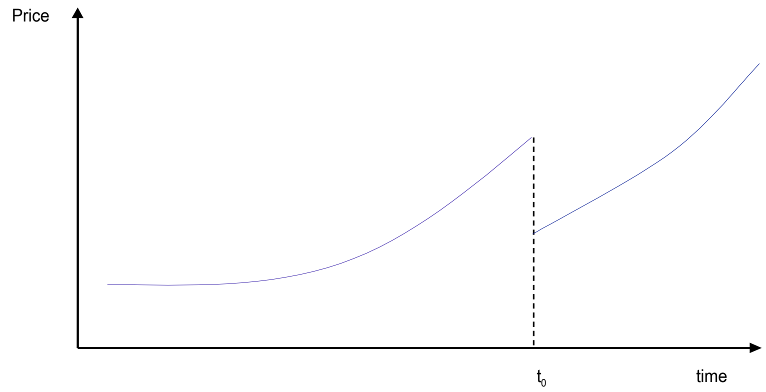


Figure 1: Chainsaw-pattern of resource prices

If the Hotelling model indeed describes the dynamics taking place in the crude oil market, a discontinuous jump in the price of crude oil should be detectable given that the following two prerequisites are satisified:

- The finding was unanticipated.
- The finding was large enough.

The following two sections explain the identification strategy for unanticipated discoveries and determine the expected decline in the price of the resource after a change in known reserves.

# 3 Identification Strategy

A sudden decline in the price of a non-renewable resource to discovery news should only be detectable if the discovery was not anticipated. Thus, the challenge in testing this hypothesis is the identification of the degree of anticipation of a resource finding, i.e. the degree to which the finding was surprising for the market.

While experts might be aware of the existence of reservoirs some time before the discovery becomes public knowledge, it is the point in time when the market actually learns about the finding that a price decline should be observable.[c] However, the price reaction depends on the market's prior beliefs regarding the likelihood of a resource finding. Only if a sufficient amount of new, i.e. surprising, information has entered the market, a significant price reaction should be visible. Thus, one needs to control for expectations present in the market prior to the discovery announcement. While the expectation of markets regarding the likelihood of an event can usually be inferred from analyst statements, no such publicly available information exists on the timing and likelihood of reserve discoveries. In order to substitute for these analyst forecasts, we infer market's expectation on the basis of the reaction that stock prices of oil companies show on the day where the discovery is announced. If the announcement of an oil discovery leads to a return on the share price of the announcing oil company that is unusually high, we infer that the discovery has not been anticipated by the market and declare the discovery to be an "unanticipated" one.

## 3.1 Method

We apply the event study methodology to identify the degree of anticipation in discovery announcements as it is the primary tool to test the arrival of new information in markets. The idea of an event study is to compare the return on the day of an event with some benchmark return and determine whether the deviation is significant. An abnormal return can thus be taken as evidence that the price of a company (i.e. its discounted, expected cash flows) has significantly changed due to the arrival of some piece of information.[d] In our case, we investigate whether the arrival of an update of information regarding the size of an oil field did change the value of a company in a significant way.

We determine the benchmark return in a so-called market model following Fama et al. (1969) and introduce dummy variables around discovery days.[e] The market model relates changes in the price of a company to general market movements and the release of the company announcement. A significant estimate of the dummy variable coefficient is interpreted as an

[c] This is equivalent to assuming a strong-form efficiency of the financial market, see e.g. Fama et al., 1969.

[d] Note that the value of a company and thus its cash flows is, amongst others, determined by the price of the product, quantities sold and costs of producing the quantity. In the case of oil companies, expected earnings are rated against the current cost of exploration and the expected cost of extraction. A significant change in the value of the company thus indicates that there is significant profit to be made even after considering the costs related to the development of and production from the field.

[e] Mckenzie et al. (2004) illustrate that the introduction of a dummy variable to measure the deviation on event days from the benchmark is equivalent in the power of test and the result using the cumulative abnormal return model.

abnormal return. In detail, we estimate the following regression:

$$R_{k,t} = \alpha_k + \beta_k R_{m_k,t} + \sum_{i=1}^{L_k} \gamma_{i,k} D_{i,k,t} + e_{k,t}. \tag{10}$$

$R_t$ is the return at time $t$ for the stock of company $k = 1, ..., K$.[f] $R_{m_k}$ is the market index corresponding to the primary listing of the company stock. The dummy variable $D_k$ takes the value of one on the discovery day of field $i$, denoted as $t = t_i^*$, if company $k$ has participated in the discovery of field $i$ and zero otherwise.[g] $L_k$ denotes the total amount of discoveries company $k$ has participated in. The error term follows an AR(1) process with $e_{k,t} = \rho_k e_{k,t-1} + u_t$ where $u_t \sim N(0, 1)$. $\alpha$, $\beta$ and $\gamma$ are coefficients and are estimated with the GLS Prais-Winsten procedure (Greene, 2008).

### 3.2 Data

Preliminary evaluations have shown that only findings of the size of *Giant* oil fields are in general large enough to have a measurable effect on the price. This class of oil fields contains the largest findings worldwide, with oil fields containing a minimum of 500 million barrels of ultimately recoverable resources. For this study, we consider only *Giant* oil fields discovered after 1990 as it has proven difficult for earlier discoveries to determine their exact discovery data. The names of Giant oil fields were taken from Mann et al. (2007) and Halbouty (2003). Table 5 in the Appendix displays the names, the region and the estimated size of the discovery at the time of the news announcement.

Within the last 50 years, the number of *Giant* oil field discoveries has been declining. Only about twenty have been found within the years 2000-2006 in comparison to 120 in the decade from 1960-1969 (see Figure 2). All in all, only 1% of all oil fields found today actually belong to this class of oil fields. However, production from these fields are essential for world oil supply as these oil fields contribute to world oil production by 60% (Halbouty, 2007). Judging from these discovery rates, crude oil has become scarcer and the finding of additional *Giant* oil field accordingly more valuable. From 1990 until 2005, a total of 49 Giant oil fields was discovered (Robelius, 2007).

[f] $R_t = \frac{P_t - P_{t-1}}{P_{t-1}}$ with settlement price $P_t$ on day $t$.

[g] As usual for event studies, we build an event window around the actual event:

$$D_{i,t} = \begin{cases} 1 & \text{if } t_i^* - 1 \leq t \leq t_i^* + 1 \\ 0 & \text{otherwise} \end{cases} \tag{11}$$

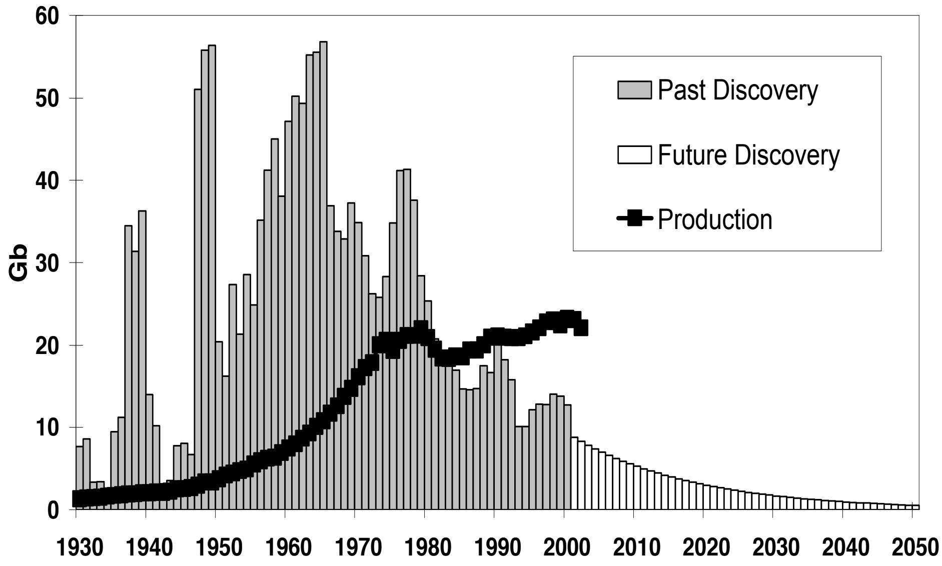


Figure 2: Discovery trends with past production and extrapolated future discovery of conventional oil; source: Campbell, 2003

Discovering an oil field has to be understood as a process involving several steps (Figure 3). After the successful completion of each step, the media is informed and the market learns more about the likelihood of a future discovery. Among the different announcements, the one containing a statement regarding the expected size of the field is of particular importance. It gives company investors an official statement on the outlook on future earnings and oil market investors an update on the amount of reserves that will become available to the market in the future.[h] Thus, it is the point in time where an adjustment to the currently held set of information regarding the scarcity of crude oil takes place.

Accordingly, the effective discovery day was determined as the day at which at least one of the involved companies officially announced the finding of the *Giant* oil field. This announcement had to appear in Platt‘s Oilgram News and in either the London Stock Exchange Aggregated Regulatory News Service or Thomson Financial News to ensure oil as well as stock market investors to have read the news. The announcement had to contain an estimate of the size of the field or a statement from which the finding of a *Giant* could be inferred. For 35 fields, it was possible to collect an announcement that satisfied the above criteria. A total of 38 publicly

[h]Note that US companies can be held credible for wrong information released in corporate news releases.

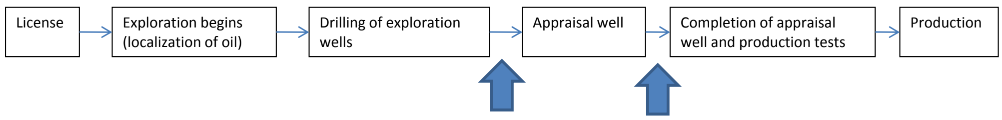


Figure 3: Discovery process and Announcements

traded companies participated in the discovery of these fields. Data on stock prices from which series of daily returns are created are taken from datastream and consist of end-of-the-day data.[i] As stock market indices, the country-specific Dow-Jones index series is used.[j]

### 3.3 Result

Table 1 displays the 20 fields for which an abnormal return on the stock price of at least one involved company could be detected. The abnormal return ranges between 0.4% in case of the Bonga discovery by Eni and 4.8% after the discovery announcement of Tupi by Petrobras. The market index is highly significant in all but four cases and the adjusted $R^2$ is for most regression in a normal and appropriate range (between 20% and 80%).

We infer from the reaction of the share prices that these 20 announcements contained a sufficiently large amount of new and surprising information as to change the earnings prospect of the company in a significant way. Given this piece of evidence, we regard the oil field findings as "unanticipated by the market". In the next step, we need to derive the expected price decline corresponding to the reserve additions.

## 4 How large should the decline in the price of crude oil be?

While the shadow cost of resource extraction is assumed to adjust to any kind of news regarding the resource stock, not every adjustment is large enough to cause a measurable shift in prices.

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[i] Returns, $R_{k,t}$ are computed as $R_{k,t} = \frac{P_{k,t} - P_{k,t-1}}{P_{k,t-1}}$ where $P_{k,t}$ is the end-of-the-day settlement price of the share as traded in the market of the company's primary listing.

[j] Note that the market of the primary listing of oil companies differ. We select the stock market index corresponding to each company's primary listing.

| Field $i$ | Company $k$ | $\beta_{m_k}$ | $\gamma_{i,k}$ | N / $R^2$ |
|---|---|---|---|---|
| Akpo | Petrobras | 1.121*** (0.011) | 0.019** (0.008) | 4165 / 0.71 |
| Azar | Lukoil | 1.044*** (0.014) | 0.007** (0.005) | 3136 /0.87 |
| Bonga | Eni | 0.937*** (0.027) | 0.004* (0.002) | 3700 / 0.49 |
| | Shell | 0.879*** (0.019) | 0.005*** (0.002) | 4719/0.53 |
| Buzzard | BG | 0.932*** (0.017) | 0.003** (0.020) | 4720/ 0.27 |
| Carioca | Petrobras | | 0.004* (0.002) | |
| Dalia | Elf | 0.312* (0.143) | 0.030** (0.015) | 4718 / 0.085 |
| Erha | Shell | | 0.021** (0.009) | |
| Girassol | BP | 0.955*** (0.024) | 0.009*** (0.002) | 4720 / 0.38 |
| | Norskhydro | 1.198*** (0.016) | 0.007*** (0.003) | 7827 / 0.70 |
| Gumusut | ConocoPhillips | | 0.008*** (0.001) | |
| Jack | Devon Energy | 0.809*** (0.026) | 0.025** (0.013) | 4720 / 0.17 |
| Kashagan | ConocoPhillips | | 0.011* (0.006) | |
| | Exxon | 0.739*** (0.031) | 0.011*** (0.002) | 4720 / 0.31 |
| | Total | 0.483* (0.211) | 0.011* (0.008) | 4719 / 0.23 |
| Kaskida | Anadarko | 0.888*** (0.015) | 0.006* (0.051) | 4720 / 0.19 |
| Knotty Head | BHP Billiton | 1.319*** (0.020) | 0.007*** (0.008) | 4720 / 0.49 |
| PengLai | ConocoPhillips | | 0.019** (0.008) | |
| Tahiti | Enterprise Oil | -0.004 (0.035) | 0.047*** (0.012) | 2704 / 0.006 |
| Tiber | Petrobras | | 0.014** (0.007) | |
| Tupi | BG | | 0.047*** (0.005) | |
| | GalpEnergia | 0.882*** (0.063) | 0.122** (0.062) | 855/ 0.36 |
| | Petrobras | | 0.048*** (0.010) | |
| Ursa | ConocoPhillips | 0.786*** (0.034) | 0.003* (0.002) | 4719/ 0.25 |
| Usan | Esso | 0.138 (0.074) | 0.009*** (0.003) | 4718 / 0.022 |
| WestSeno Complex | Mobil | 0.136** (0.050) | 0.006* (0.006) | 2061 / 0.006 |

standard errors in parentheses
$^{*}$ $p < 0.1$, $^{**}$ $p < 0.05$, $^{***}$ $p < 0.01$
Note: only abnormal returns are displayed.

Table 1: Unanticipated discoveries

Log-differentiating equation (8) results in an expression that relates the percentage change in the stock level to the percentage change in the initial price level, $p_0$:[k]

$$\widehat{p}_0 = -\frac{1}{|\eta|}\widehat{S}_0 \tag{12}$$

The socially optimal solution defines that a one percent increase in the resource stock leads to a decline of $\frac{1}{|\eta|}$- percent in the initial price of the non-renewable resource.[l]

In empirical analyses on asset prices, the percentage change in the price of an asset is usually referred to as the return on the price. Thus, we will investigate how the return - denoted as $R$ - on the price of crude oil is influenced by a change in the known reserve stock. Equation (8) is re-phrased as $R^e = -\frac{1}{|\eta|}\widehat{S}_0$ where $R$ refers to return and "$e$" to the fact that it is an expected return rather than an observed one.

## 4.1 Data

### 4.1.1 The Reserve Stock

Official reserve estimates as provided by the IEA show that the resource stock has been increasing steadily over time: they have doubled from 645 bn barrels to more than 1 300 bn barrels in 2009. While this source is often cited in newspapers, experts doubt the validity of these numbers as they are provided by countries themselves and are not evaluated by independent sources (see eg.g Hamilton, 2008). Among the various independent assessments of oil reserves, the one by Laherrere and Campbell is known to be the most accurate (Bentley, 2002). According to their work reserves have been increasing until 1980 and have since declined.[m] As these estimates count among the most trustworthy among experts, we use it as the basis for our calculations. Table 2 displays estimated crude oil reserves according to Laherrere (2007). According to these figures, the finding of a barrel of oil has increased in value by 28%.

[k] We assume a constant demand function here.

[l] Note that the term "initial" price does not refer to the price at the beginning of resource exploitation. "Initial" refers to the price level (pinned down by the stock of the resource, the interest rate and the demand elasticity) from which the price starts raising following equation (5). Any change in one of the underlying parameters changes this "starting" value.

[m] These estimates are computed on the basis of the 2P-measure. Official reserve statistics also suffer from a dis-harmonized application of reserve definitions: while the US and the OPEC countries use the 1P measure, countries in the former Soviet Union apply the 3P measure.

Table 2: Technical Estimate of Crude Oil Reserves (in bn barrels)

| Year | 1990 | 1991 | 1992 | 1993 | 1994 | 1995 | 1996 | 1997 |
|---|---|---|---|---|---|---|---|---|
| approx. Reserves | 1030 | 1015 | 1000 | 985 | 970 | 955 | 940 | 925 |
| Year | 1998 | 1999 | 2000 | 2001 | 2002 | 2003 | 2004 | 2005 |
| approx. Reserves | 910 | 895 | 880 | 865 | 850 | 835 | 820 | 805 |

Source: Laherrere, 2007.

These estimates are used to compute the percentage change in reserves due to our unanticipated discoveries (See Column (4) of Table 5).

#### 4.1.2 Demand Elasticity

In order to be able to compute the decline in the price of crude oil to the finding of a *Giant* oil field, assumptions regarding the demand elasticity of crude oil need be made. While many attempts have been made to determine the size of crude oil demand elasticity, there is no accordance as to how high this value actually should be. Differences in results arise from the model specification, the estimation methodology and the sample period. Despite the differences in results, there is a consensus that demand is highly price-inelastic in the short run and less inelastic but still small in the long run. Krichene (2002) obtains estimates from a simultaneous equation model where world crude oil demand and world supply are modeled simultaneously. Demand elasticities for the short and long run are estimated for three sample periods, covering the entire time horizon for which data is available (1918-1999), and two sub-periods corresponding to the time before and after the oil crises (1918-1973; 1973-1999). Short-run demand elasticity estimates do not differ dramatically for these three samples and range between $-0.02$ (1973-1999) and $-0.08$ (1918-1973). Long run demand elasticity estimates are $-0.05$ (1918-1999), $-0.13$ (1918-1973) and almost zero (1973-1999). In a follow-up study, Krichene (2006) extends the data set to the year 2004, preserving the same set up and methodology. A remarkable difference occurs for the result on the short run demand elasticity in the sample period 1973-2004 as it is estimated to be much lower ($-0.003$) than before. Long run demand elasticity is estimated as $-0.27$ (1918-2004), $-0.32$ (1918-1973) and -0.26 (1974-2004). Both contributions show a drop in the demand elasticity for the latest sample period (1973-1999/2004) compared to the other two sample periods (1918-1999/2004; 1918-1973). Krichene (2006) attributes this drop to the fact that the oil price shocks "compressed long-run demand to a level that was highly inelastic to price changes, thereby creating a kink in the long-run demand curve" (pg. 11).

Similar estimates for the demand elasticity can be found in Hamilton (2008) and Cooper (2003). Hamilton (2008) estimates the long run demand elasticity to be $-0.26$. Cooper (2003) obtains elasticity estimates from a multiple regression model using data from 1971-2000 for 23 different countries. The average demand elasticities for these 23 countries is $-0.05$ for the short run and $-0.21$ for the long run. Despite the differences in estimates, most of the studies tend to establish a highly price-inelastic demand schedule in the short run and a more elastic, though still lower-than-unity demand price elasticity in the long run. Table 6 compares the different studies and results.

We use both, an estimate for the short run demand elasticity ($-0.05$) and one for the long-run demand elasticity ($-0.26$) to compute the expected change in the oil price due to reserve additions.

### 4.2 Result

Columns (1) and (2) of Table 7 display the socially optimal decline in the price of crude oil to oil field discoveries assuming an estimate of the short-run and long-run elasticity estimate, respectively. The results differ quite substantially: while the expected rate of price decline ranges between 1.0% and 28% using the short-run elasticity estimate, it varies between 0.29% and 6.67% assuming an estimate of the long-run elasticity. For example, the biggest oil field that has been discovered since 1990, Kashagan, should have resulted in a negative return of $-28\%$ assuming the short run elasticity estimate, $\eta = 0.05$ and $-6.67\%$ assuming a long run elasticity of $\eta = 0.21$. From these results, it is clear that the size of the socially optimal price decline heavily depends on the assumption made regarding the demand elasticity estimate.

## 5 Does the Market react optimally to Oil Field Discoveries?

In the theoretical model in section 2, the first order condition for a welfare maximizing solution postulated the price to be exactly equal to the shadow cost. This result was based on assumptions such as zero extraction costs and, implicitly, also a constant extraction technology. If we want to trace down an observed change in the price of crude oil to a decrease in scarcity, these assumptions need to be translated in a suitable way into the empirical set-up. In addition to extraction costs and technology, changes in the interest rate may affect the initial price level (equation 8). Thus, in order to be able to compare a price change derived from the model with the one observed, shifts in the interest rate need to be controlled for, as well.

We implement the assumptions of zero extraction costs and no change in the extraction technology in the empirical set-up by investigating price changes over a very short time horizon. As in the model, we thereby assume that the price adjusts to lower scarcity as soon as the information becomes available to the market. Such a short-term investigation reduces the likelihood of changes in the extraction cost or extraction technology having an impact on the price.

Changes in the interest rate are controlled for using risk-adjusted returns of crude oil. In addition, five-day-average risk adjusted returns of the price of crude oil are computed to check the robustness of the results and to investigate the behavior of the return around the event day.

As the goal of the study is an assessment of the markets optimal reaction to news about decreased scarcity, we measure the degree of price adjustment for each field, using "rationality-parameters": these parameters illustrate whether the market reacted optimally or whether an overreaction or an underreaction took place.

### 5.1 Method

We first compute a risk-adjusted return, controlling for general market movements and changes in the risk-free interest rate. We therefore regress the return on crude oil on a commodity market index and the risk free rate:

$$R_{i,t} = \alpha_i + \beta_i R_{m,t} + \gamma_i R_{f,t} + e_{i,t} \tag{13}$$

where $i$ denotes the discovery announcement of field $i$, $R_m$ is the commodity market index and $R_f$ a proxy of the risk free rate. We account for heteroscedasticity and autocorrelation in the estimation procedure. The residual, $\widehat{e}_{i,t}$, on the day of a discovery announcement, $t = 0$, is taken as the second measure of price decline:

$$R_t^{(1)} = \widehat{e}_{i,t} = \widehat{R}_{i,t} - \widehat{\alpha}_i - \widehat{\beta}_i R_{m,t} - \widehat{\gamma}_i R_{f,t} \tag{14}$$

The five-day risk-adjusted average return uses the residuals gained in equation (15) and computes the average over an event window one day before and three days after the actual event day, $t = 0$:

$$R_t^{(2)} = \frac{1}{5} \sum_{t=-1}^{t=3} \widehat{e}_{i,t} \tag{15}$$

The deviation of the market from the socially optimal solution is measured in percentages using the one-day risk adjusted return from equation

(14). These rationality-parameters are computed for the short- and long-run demand elasticity estimate:

$$\lambda^1 = \frac{R_t^{(i)}}{R^e_{(|\eta|=0.05)}} \tag{16}$$

and

$$\lambda^2 = \frac{R_t^{(i)}}{R^e_{(|\eta|=0.21)}}. \tag{17}$$

where $\lambda^j$ is the rationality parameter measuring the deviation of observed returns from the social optimum for the short-run demand elasticity ($j = 1$) and the long-run elasticity ($j = 2$). In an optimal solution, $\lambda$ is equal to one. Figure 4 illustrates this case. An overreaction of the market is indicated by $\lambda > 1$, an underreaction by $\lambda < 1$.

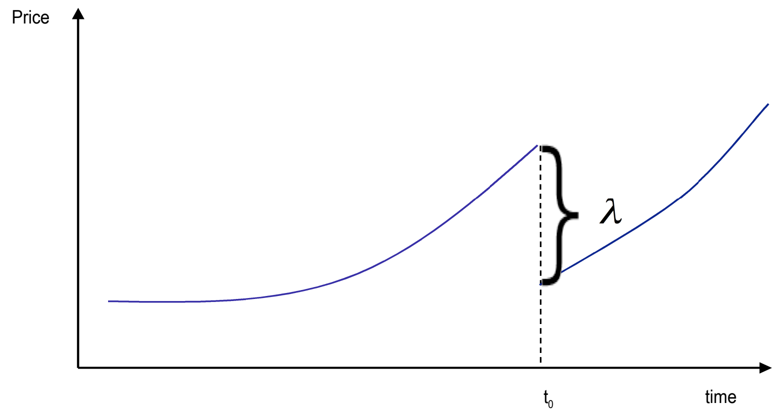


Figure 4: Determining the distance from the optimal solution

## 5.2 Data

We use the price series for the contract with the highest trading volume, the light sweet crude oil price for delivery in one month traded on the NYMEX as proxy for the crude oil price. The CRB commodity index by the Commodity Research Bureau is taken as market index. The U.S. federal funds rate is taken as risk-free rate. All series are taken from Datastream and consist of end-of-the-day (settlement) prices.

### 5.3 Result

Columns (3) and (4) of Table 7 display the results for the observed price decline. The average residual return (Column 3) is negative and declines by $-0.861\%$ on days of discovery announcements. The three-day average residual return (Column 4), in contrast, is positive. Thus, while a price decline is observable on days of discovery announcements, the adjustment is immediately followed by a subsequent price increase. This can also be seen from Figure 5. It displays the average return computed across all 20 discovery announcements for a window of one day before and three days after the actual announcement, together with their 95%- standard error bands. The average return the day before the announcement is positive and drops below zero on the actual event day.[n] During the subsequent three days, the average return increases and is positive again. Thus, on average, the price drops on the event day and increases thereafter, in line with Hotelling's predictions. Table 3 displays the average return for each day of the five-day event window.

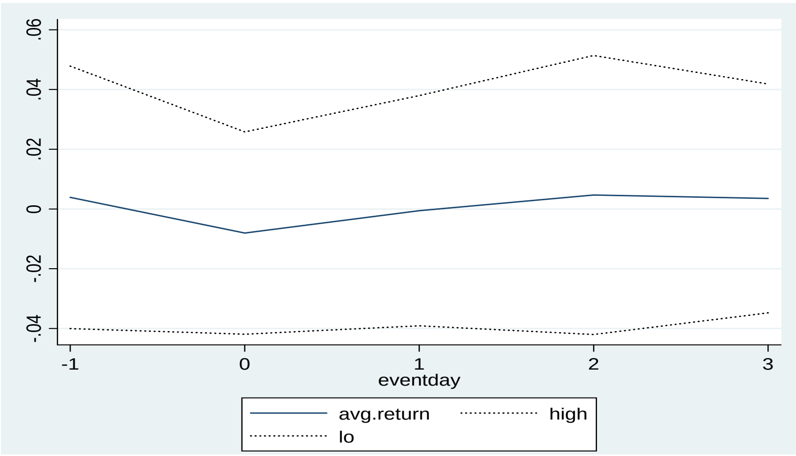


Figure 5: Average return during Event Window

Table 3: Average Return (in %) during Event Window

| Day | $t=-1$ | $t=0$ | $t=1$ | $t=2$ | $t=3$ |
|---|---|---|---|---|---|
| $R_t^{(1)}$ | 0.4 | -0.81 | -0.06 | 0.47 | 0.35 |

The rationality parameter comprises the information provided by expected and observed returns. Figure 6 plots the actual price decline against

[n]Note that the event day is defined as the announcement day and denoted by 0 on the x-axis.

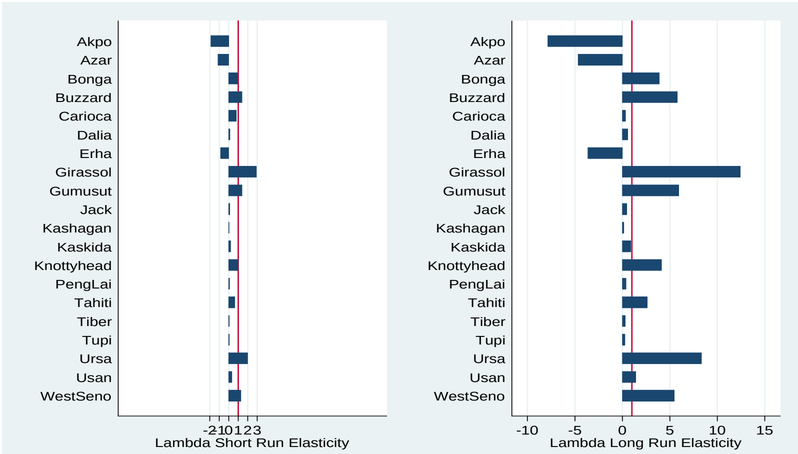


Figure 6: Deviations from Expected Behavior

the socially optimal decline for each field. The straight line serves as benchmark and indicates the socially optimal price decline (i.e. $\lambda = 1$). The variation of $\lambda$ decreases with demand inelasticity: smaller values of the demand elasticity result in much smaller variation of $\lambda$ than larger ones. Only the announcements of four fields- Akpo, Azar and Erha - are associated with positive returns on crude oil. The announcements of all other fields are associated with a negative return.

Table 4: Summary Statistic of Rationality Parameters

| Rationality parameter | Mean | St.dev. | T-test |
|---|---|---|---|
| $\lambda_1^1$ | 0.545 | 1.082 | -0.421 |
| $\lambda_1^2$ | 2.041 | 4.545 | 0.229 |

Table 4 displays summary statistics for the rationality parameters. $\lambda_1^1$ is smaller than one which indicates that the market did underreact compared to the nominal price reaction. $\lambda_1^2$, in contrast, is larger than one (2.041). However, both parameter estimates are not significantly different from one as the t-test reveals. Thus, the reaction of the market to discovery announcements does not significantly deviate from a socially optimal behavior.

## 6 Conclusion & Discussion

This paper provides a direct test of the static efficiency condition of the Hotelling rule. Its validity is a necessary prerequisite for non-renewable resource prices to be optimal. Unanticipated discoveries of additional reserve reservoirs, such as crude oil field discoveries, are a model case to conduct a test of the static efficiency condition: while theory expects a sudden decline in the price of the resource to news about a decline in scarcity, the increase of the user cost over time is not affected. Thus, it is possible to concentrate on the price reaction at distinct points in time instead of having to investigate the entire price path.

A test on the reagibility of the crude oil price to oil field discoveries involved four steps: first, the simple Hotelling model is used to illustrate the interdependence of the price and the stock size. It serves as starting point to derive the expected price decline to the resource finding. Secondly, among all discovery news since 1990 those news containing a significant amount of new information regarding the size of the discovery are identified and classified as unanticipated. Third, for days of unanticipated discoveries, the observed price decline is computed. Last, the deviation from the socially optimal solution is computed using so-called rationality parameters.

We observe for the average of all unanticipated discoveries a price decline of $-0.861\%$ on days of discovery announcements. The price decline is temporary as predicted by the Hotelling model: already two days after the discovery announcement, the price starts rising again.

The size of the price adjustment is not inconsistent with the expected decline according to the socially optimal solution: even for varying values of the demand elasticity, the rationality parameters cannot be shown to significantly differ from the socially optimal solution. For a very low value of the demand elasticity (short-run estimate), the market price adjusts on average by 55%. Using a higher value of the demand elasticity (long-run estimate), the market price even overshoots the socially optimal solution (2.04). Clearly, the deviation from the socially optimal solution varies with the choice of the demand elasticity parameter.

All in all, we find patterns in the price of crude oil on days of discovery announcements which are in line with the static efficiency condition by Hotelling (1931). Thus, there is no reason to believe that the market does not value reserve findings and scarcity as a price component of non-renewable resources.

The study will be extended to include other types of crude oil and longterm futures contracts .

# 7 Appendix

## 7.1 Details on Giant Oil Fields

Table 5: List of Giant Oil Fields

| Name | Country / Region | Discovery Year | Size (mio URR) | % of world reserves |
|---|---|---|---|---|
| Agbami | West Africa | 1999 | 800 | 0.09 |
| Akpo | West Africa | 2000 | 900 | 0.1 |
| Amenam | West Africa | 1990 | 700 | 0.07 |
| Azadegan | Iran | 1999 | 5200 | 0.58 |
| Azar | Iran | 2005 | 500 | 0.06 |
| Bonga | West Africa | 1996 | 1000 | 0.11 |
| Buzzard | North Sea | 2001 | 500 | 0.06 |
| Carioca | Brazil | 2007 | 10 000 | 1.3 |
| Crazyhorse[o] | Gulf of Mexico | 1999 | 1000 | 0.11 |
| Crazyhorse North | Gulf of Mexico | 2001 | 500 | 0.06 |
| Cupiagua / Cusiana | Colombia | 1991 / 1992 | 1600 | 0.16 |
| Dalia | West Africa | 1997 | 1 000 | 0.11 |
| Elephant | Libya | 1998 | 700 | 0.08 |
| Erha | West Africa | 1990 | 700 | 0.07 |
| Gindungo | West Africa | 2003 | | |
| Girassol | West Africa | 1996 | 700 | 0.07 |
| Gumusut | Malaysia | 2004 | 550 | 0.07 |
| Hungo[p] | West Africa | 1998 | 700 | 0.08 |
| Jack | Gulf of Mexico | 2006 | 3000 | 0.38 |
| Kashagan | Kazakhstan | 2002 | 12 000 | 1.4 |
| Kaskida | Gulf of Mexico | 2006 | 3000 | 0.38 |
| Knotty Head | Gulf of Mexico | 2005 | 500 | 0.06 |
| Landana | West Africa | 1998 | 500 | 0.05 |
| Palogue | Indonesia | 2003 | 1000 | 0.12 |
| Papa Terra | Brazil | 2005 | 1000 | 0.12 |
| Peng Lai | China | 2000 | 500 | 0.06 |
| Raghib | Saudi Arabia | 1990 | 600 (?) | 0.06 |
| Roncador | Brazil | 1996 | 3 200 | 0.34 |
| Tahiti | Gulf of Mexico | 2002 | 500 | 0.06 |
| Tiber | Gulf of Mexico | 2009 | 500 | 0.07 |
| Tupi | Brazil | 2007 | 8 000 | 1.1 |
| Ursa | Gulf of Mexico | 1995 | 500 | 0.05 |
| Usan | West Africa | 2003 | 500 | 0.06 |
| West Seno Complex | Indonesia | 1998 | 600 | 0.07 |

Source: Mann et al., 1990, Robelius, 2007; company data, secondary sources.

## 7.2 Overview of Demand Elasticities in the Literature

Table 6: Literature Results on Price Elasticity of Demand

| Name | Sample Size | Technique | Country | Short-run | Long-run |
|---|---|---|---|---|---|
| Demand Elasticity for Crude Oil | | | | | |
| Krichene (2002) | 1973-1999 | VEC | world level | -0.02 | -0.005 |
| | 1918-1999 | VEC | world level | -0.02 | -0.05 |
| Gately and Huntington (2002) | 1971-1997 | | OECD | -0.04 | -0.64 |
| | 1971-1997 | | non-OECD | -0.01 | -0.18 |
| Cooper (2003) | 1971-2000 | 2 SLS | average of 23 countries | -0.05 | -0.21 |
| Krichene (2006) | 1970-2005 | VEC | world level | -0.03 | -0.08 |
| Demand Elasticity for Gasoline | | | | | |
| Dahl and Sterner (1991) | | | | -0.26 | -0.86 |
| Espey (1998) | | | | -0.26 | -0.58 |
| Graham and Glaister (1991) | | | | -0.25 | -0.77 |
| Hughes, Knittel and Sperling (2008) | 2001-2006 | | | -0.034 | -0.077 |

## 7.3 Expected versus Observed Decline in the Price of Crude Oil

Table 7: Expected vs. Observed Decline in the Price of Crude Oil

| Field Name | Exp. Return, $R^e_{(\|\eta\|=.)}$ | | Obs. Return, $R_t^{(\cdot)}$ | |
|---|---|---|---|---|
| | $\|\eta\| = 0.05$ | $\|\eta\| = 0.21$ | $R_t^{(1)}$ | $R_t^{(2)}$ |
| | (1) | (2) | (3) | (4) |
| Akpo | -2.0 | -0.48 | 3.77 | 5.57 |
| Azar | -1.2 | -0.29 | 1.35 | 1.22 |
| Bonga | -2.2 | -0.54 | -2.1 | 1.58 |
| Buzzard | -1.2 | -0.29 | -1.68 | 1.26 |
| Carioca | -2.6 | -6.2 | -2.09 | -2.27 |
| Dalia | -2.2 | -0.52 | -0.3 | -0.82 |
| Erha | -1.4 | -0.33 | 1.2 | 2.15 |
| Girassol | -1.4 | -0.33 | -4.10 | 1.95 |
| Gumusut | -1.4 | -0.33 | -1.96 | 0.14 |
| Jack | -7.6 | -1.81 | -0.86 | -1.8 |
| Kashagan | -28.0 | -6.67 | -1.90 | -1.03 |
| Kaskida | -7.6 | -1.81 | -1.57 | -0.54 |
| Knotty Head | -1.2 | -0.29 | -2.1 | 3.1 |
| Peng Lai | -1.2 | -0.3 | -0.12 | -1.18 |
| Tahiti | -1.2 | -0.29 | -0.76 | -1.28 |
| Tiber | -1.4 | -0.33 | -0.10 | -1.76 |
| Tupi | -22.0 | -5.24 | -1.46 | 1.2 |
| Ursa | -1.0 | -0.24 | -0.2 | -0.50 |
| Usan | -1.2 | -0.29 | -0.41 | -2.35 |
| West Seno | -1.4 | -0.33 | -1.80 | 0.64 |
| Mean | -4.47 | -1.35 | -0.861 | 0.0275 |
| St.dev. | 7.34 | 2.09 | 1.63 | 1.966 |

Table 8: Columns (1) and (2) display the optimal price decline computed from section 2, for the short- and long-run demand elasticity, respectively. Columns (3) and (4) display the observed risk-adjusted one-day return and the risk-adjusted five-day average return, respectively.

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