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Does the Oil Price Adjust 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 its remaining availability. This study provides an empirical test of this hypothesis. It investigates whether the price of crude oil does adjust to unexpected news about oil field discoveries. The observed price reaction is compared with a prediction of the price decline as derived from the Hotelling model. This study finds evidence for an adjustment of the price to news about greater resource availability: the price of crude oil declines on average by 0.88% on discovery days. The degree of adjustment to the new level of scarcity is not found to differ significantly from the social optimum. Thus, there is evidence for the existence of a shadow cost component - a necessary pre-requisite for the Hotelling rule to hold.

JEL classification: Q31; Q41; Q14
Keywords: Non-renewable resources; Oil Price; Exhaustible Resources

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1 Introduction

The welfare maximizing solution for extracting a non-renewable resource by Hotelling (1931) requires two conditions to hold: First, the static efficiency condition claims that the value of extraction from the resource stock is equal to the shadow value. This price component reflects the opportunity cost of using one unit of the resource today rather than tomorrow and arises only due to the fact that the supply of the resource is finite. Second, the dynamic efficiency condition states that the optimally extracted quantity adjusts such that the shadow value increases at a rate of return comparable to an alternative investment.

Empirical tests of the Hotelling rule have conducted a test of the static and dynamic efficiency condition at the same time.[1] Due to the multitude of factors influencing the price of a resource at any time, an ex-post reconstruction of the scarcity rent and its comparison with predictions from the Hotelling model is a daunting task. Only few contributions have found evidence of the Hotelling rule.[2]

The goal of this study is to provide an alternative way of testing the Hotelling rule. This study does not attempt a reconstruction of the evolution of scarcity rent in a test of the dynamic efficiency condition. It rather focusses exclusively on a test of the static efficiency condition: it tries to find evidence for the existence of the shadow cost component in the price of a non-renewable resource but does not pay attention to its development over time. The existence of such a price component is a necessary prerequisite for an optimal evolution of resource prices and is the main criterion to distinguish the price formation of a non-renewable from that of a renewable resource.

An empirical test on the existence of the shadow cost component and thus the validity

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[1] Early contributions include Barnett and Morse (1963), Barnett (1979) and Barnett and Smith (1978; 1979).

[2] Farrow (1985), Halvorsen and Smith (1991), Young (1992) and Young and Ryan (1996) count among contributions that were not able to find any evidence for the Hotelling rule. While Miller and Upton (1985), Slade (1982), Slade and Thille (1997), Livernois et al. (2006) provide some evidence for the Hotelling rule, their studies have been derived under specific conditions or could not be confirmed by follow up-studies. See Livernois (2008) for a comprehensive survey on the empirical evidence of the Hotelling rule.

of the static efficiency condition can be conducted on the ground that a change in known scarcity must lead to a change in the price of the non-renewable resource. Unanticipated discoveries of additional resource reservoirs serve as an example of a sudden change in known scarcity: the shadow value of the resource instantaneously drops, indicating the lower opportunity cost of using the unit today, ceteris paribus. The rate of increase in the shadow price, however, must not change as the rate of return from holding the alternative investment has not changed (Dasgupta & Heal, 1979). This test is applied to and conducted for the example of the price adjustment of crude oil to unanticipated discoveries of oil fields.

While discoveries of additional resource reservoirs have been frequently mentioned as an example of how the scarcity of a non-renewable resource affects its price (e.g. Perman et al. 2003), they are one of the few factors not tested in the literature on the Hotelling rule, so far. Still, they are expected to have contributed to the development of non-renewable resource prices (Livernois, 2008). An analysis of the interrelation between known scarcity and the price of crude oil requires two crucial steps: First, the change in known scarcity needs to be unanticipated. Only if the discovery was not anticipated by the market, a sudden reaction of the price for the non-renewable resource should be detectable. We infer market's expectation regarding oil field findings from the reaction of stocks of oil companies involved in the discovery to their discovery announcements. Secondly, the finding needs to be large enough to cause a price decline. We use the Hotelling model to derive a reference value for the expected decline in the price of the non-renewable resource following an oil field discovery and compare it to the observed change in price.

We can identify 20 unanticipated oil field discoveries and investigate their impact on the crude oil market. We find that the average return on days of discovery announcements is significantly different from zero and negative (-0.88%). Furthermore, this price adjustment is not found to differ significantly from the theoretically expected price decline. Thus, we do not only find evidence for an opportunity cost component in the price of the nonrenewable resource as proposed by Hotelling (1931) but also that the market seems to value resource scarcity in a manner not different from an optimal solution.

The remainder is organized as follows: Section 2 proposes the theoretical impact of a change in the size of the resource stock on the price for the resource. Section 3 identifies the sample of unanticipated discoveries. Section 4 evaluates the adjustment of the price to its theoretical prediction. Section 5 concludes.

2 Theoretical Background & Hypotheses

The impact of a resource finding on the optimal price of a non-renewable resource is illustrated in the standard Hotelling model. The model allows to derive a prediction regarding the expected price decline to unanticipated discoveries that is used as a reference in the subsequent sections.

We assume a perfectly competitive market[3] where every resource owner maximizes revenues over time from extracting a fixed resource stock:[4]

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

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 λ_t indicates the penalty on present value profits arising from the extraction and use of an additional unit of the resource which is then foregone for future production. This component is therefore also referred to as the shadow cost or opportunity cost of resource extraction. The size of the opportunity cost of resource extraction, λ_t, is decreasing with the total resource stock: the scarcer the resource becomes, the higher is the opportunity cost of using an additional unit of the resource today,

$$\frac{\partial \lambda_t}{\partial S_t} < 0. \tag{4}$$

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[3] Note that the results remain the same under the assumption of a monopoly or an oligopoly if an iso-elastic demand curve is assumed.

[4] Dasgupta and Heal (1979) show that the consequences for the Hotelling price path remain the same if exploration is assumed to be uncertain. With the assumption of risk neutrality and a continuous stochastic process for discoveries, the level but not the expected rate of change in the resource price path is affected. Thus, for illustrational purposes, the assumption of a fixed resource stock suffices.

The first order conditions for the maximization problem described in Equation (3) read

$$\frac{\partial H_t}{\partial R_t} = p_t - \lambda_t = 0 \tag{5}$$

$$\Leftrightarrow p_t = \lambda_t$$

and

$$\frac{\partial H_t}{\partial S_t} = \dot{\lambda}_t - r\lambda_t \tag{6}$$

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

Equation (5) is known as the static efficiency condition: at every point in time, the shadow price of resource extraction, λ_t, needs to be equal to the revenue gained from extraction p_t. Equation (6) 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):

$$p_t = p_0 e^{rt} \tag{7}$$

Dasgupta and Heal (1979) investigate the effect of an unanticipated change in known resource stock on the price of the non-renewable resource: An increase in the resource stock, S, at a later date than $t = 0$ reduces the shadow cost of resource extraction, λ_t, in Equation (4). The static efficiency condition as described in Equation (5) requires the price, p_t, to adjust to the shadow cost, λ_t, in the same period of time t. The dynamic efficiency condition in Equation (6) is not affected as the rate of increase in the shadow cost is given exogenously by the interest rate, r. Thus, as long as the change in scarcity has not been anticipated, discoveries should lead to a discontinuous drop in the price of the non-renewable resource with an unaffected, subsequent rate of price increase. Recurring resource discoveries cause the well-known chain-saw pattern in resource prices (Figure 1, Dasgupta and Heal (1979), Krautkraemer (1998), Perman (2003)).[5]

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[5] An anticipated discovery, in contrast, does not lead to a discontinuous jump.

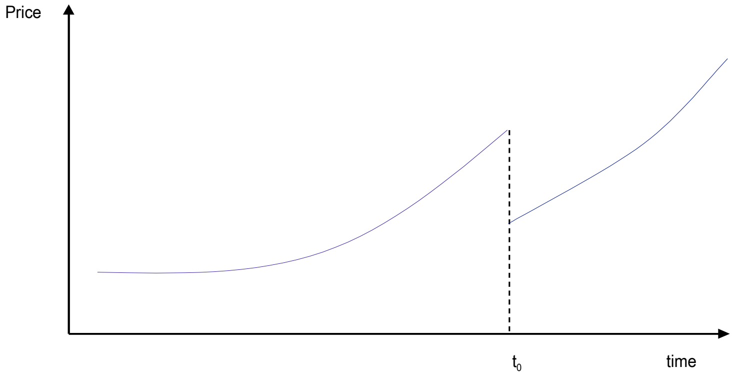

Figure 1: Chainsaw-pattern of resource prices

A more precise view on the interrelation between a change in the resource stock and the price for the non-renewable resource can be gained with an explicit assumption on the demand function.

Assuming an iso-elastic demand curve,

$$D_t = p_t^{-\eta} \tag{8}$$

and imposing the equilibrium condition of total resource extraction by the end of the horizon, i.e. $\int_0^\infty D_t = S_0$, the initial price level solves as

$$p_0 = \left(\frac{1}{\eta r S_0} \right)^{\frac{1}{\eta}} \tag{9}$$

The initial price level depends on the stock size, the interest rate and the demand elasticity.

From this equation, it is possible to derive the reference value for the expected change in the price of crude oil after additional reserve discoveries. Log-differentiating Equation (9) yields

$$\widehat{p} = -\frac{1}{\eta} \widehat{S} \tag{10}$$

where $\widehat{p}$ denotes the percentage change in the price of the resource and $\widehat{S}$ the percentage change in the resource stock. Equation (10) postulates that, in a socially optimal solution, a one percent increase in the resource stock leads to a decline of $\frac{1}{\eta}$- percent in the price of the non-renewable resource. The demand elasticity regulates the size of the price decline that is necessary for the additional quantities to be used until the end of the planning horizon.

From Equation (10) a prediction of the optimal price decline is computed after each unanticipated resource discovery, i. The prediction serves as a benchmark to judge whether the observed price decline has been large enough. The ratio of observed to expected price decline measures the degree of adjustment to each unanticipated discovery i:

$$\widehat{\theta}_i = \frac{\text{observed price decline after discovery } i}{\text{expected price decline of discovery } i}. \tag{11}$$

As a decline in the price of crude oil should only be observed for discoveries that were not expected by the market, the next step consists in identifying such unanticipated discoveries.

3 Identifying the Sample of Unanticipated Discoveries

The following section first describes the type of oil field discoveries selected in the study and continues with testing the degree to which each finding was anticipated by the market. The results of the identification are presented in the last subsection.

3.1 Selection of Sample

For this study, *Giant* oil fields discovered after 1990 are considered. This class of *Giant* oil fields contains the largest findings worldwide, with oil fields containing a minimum of 500 million barrels of ultimately recoverable resources.[6] *Giant* oil fields are important for the world crude oil supply as they contribute by about 60% to world oil production. Only 1% of all oil fields found today actually belong to this class of oil fields (Halbouty, 2007). Within the last 50 years, the number of *Giant* oil field discoveries has been declining. From 1990 until 2005, a total of 49 Giant oil fields were discovered (Robelius, 2007) in comparison to 120 in the decade from 1960-1969 (see Figure 2). Judging from these discovery rates, crude oil has become scarcer and the finding of additional *Giant* oil fields accordingly more valuable. The names of Giant oil fields were taken from Mann et al.

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[6] Their size in relation to the total resource stock is shown later in this section.

(2007) and Halbouty (2003). Table 3 in Section 4.2 displays the name of *Giant* oil fields considered in this study, their location and their estimated size at the time of the news announcement.

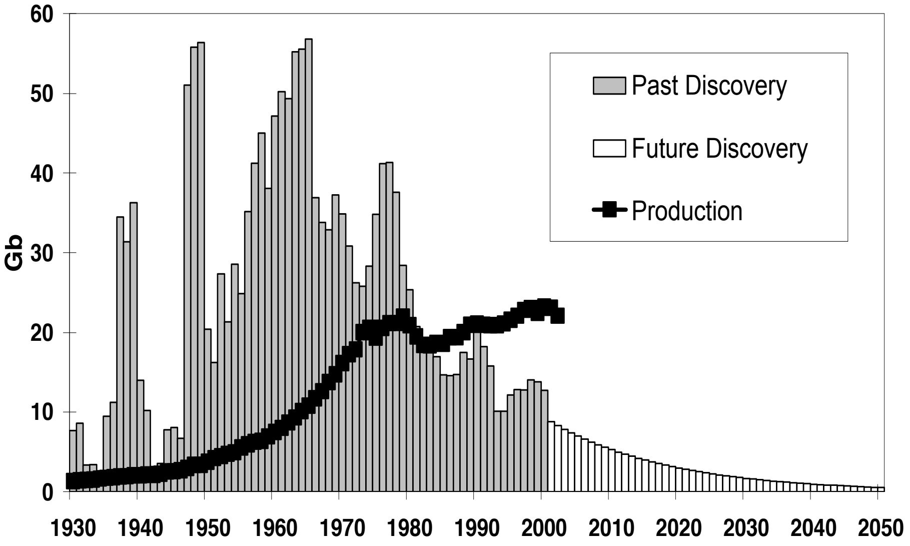

Figure 2: Discovery trends with past production and extrapolated future discovery of conventional oil; source: Campbell, 2003

Discovering an oil field has to be understood as a process involving several steps. After the successful completion of each step, the media is informed and the market updates its prior information concerning 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.[7] Thus, it is the point in time where an adjustment to the current perception of the scarcity of crude oil takes place. Consequently, the effective discovery day was chosen as the day on which one of the involved companies officially announced the finding of the *Giant* oil field. This announcement had to be made public through an international news agency and was selected through LexisNexis. 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.

A sudden decline in the price of a non-renewable resource to discovery news should

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

only be detectable if the discovery was not anticipated. Thus, the challenge in testing the hypothesis of a shadow cost component in the price of crude oil requires the identification of the degree of anticipation of the particular finding, i.e. the degree to which the finding was surprising for the market. 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. Thus, expectations present in the market at the time of the discovery announcement cannot be easily reconstructed, ex post. In order to substitute for the lack of analyst forecasts, we infer market's expectation on the basis of the reaction that stock prices of oil companies show on the day that 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.[8] [9]

For 35 fields, it was possible to collect an announcement that satisfied the above criteria. A total of 38 publicly traded companies participated in the discovery of these fields.

3.2 Test on Anticipation

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 (Fama et al. 1969). 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.[10] In our case, we investigate whether the arrival of new information

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[8] While experts might be aware of the existence of reservoirs some time before the discovery becomes public knowledge, it is unlikely that this privately held knowledge moves the price of crude oil. Thus, this analysis focusses on the point in time when the market actually learns about the finding. This is equivalent to assuming a semi-strong-form efficiency of the market, see e.g. Fama et al., 1969.

[9] This identification strategy reduces the sample further as oil fields need to be discovered by a consortium which includes at least one publicly traded company.

[10] 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.

regarding the finding of an oil field and its potential size changes 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) but determine the existence of an abnormal return by introducing dummy variables for discovery days.[11] 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 abnormal return. In detail, we estimate the following regression:

$$R_{k,t} = \alpha_k + \beta_k R_{m_k,t} + \sum_{i=1}^{L_k} \gamma_{i,k} D_{i,k,t} + e_{k,t}. \tag{12}$$

$R_{k,t}$ is the return at time t for the stock of company $k = 1, ..., K$.[12] 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.[13] 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 $u_t \sim N(0,1)$. α_k, β_k and γ_k are coefficients and are estimated with the GLS Prais-Winsten procedure (Greene, 2008).

Data on stock prices from which series of daily returns are created are taken from datastream and consist of end-of-the-day data.[14] As stock market indices, the country-specific Dow-Jones index series is used.[15]

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[11] McKenzie et al. (2004) illustrate that the introduction of a dummy variable to measure the deviation from the benchmark on event days is equivalent in the power of the test statistic to the cumulative abnormal return method originally used by Fama et al. (1969).

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

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

$$D_{i,t} = \begin{cases} 1 & \text{if } t_i^* - 1 \leq t \leq t_i^* + 1 \\ 0 & \text{otherwise} \end{cases} \tag{13}$$

[14] 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 of company k as traded in the market of the company's primary listing.

[15] 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.

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.

Table 1: Unanticipated discoveries

Field i	Company k	β_{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.

We infer from the reaction of the share prices that these 20 announcements contained a sufficiently large amount of new and surprising information regarding the existence and size of the oil field discovery so 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". These 20 discoveries are used to derive the prediction of the price decline and its observed counterpart.

4 Is There Evidence For a Price Decline in Line With The Theoretical Prediction?

This section first computes the predicted oil price decline as derived from the Hotelling model before the actual decline in the price is determined. The last part of the section compares both values.

4.1 The Predicted Price Decline

Equation (10) forms the basis to compute the predicted oil price decline. It relates the percentage change in the price of crude oil to the percentage change in the resource stock times the demand elasticity. In order to compute this value, we need an estimate of the demand elasticity and an estimate of the size of the resource stock at the time of each discovery.

As the percentage change in the price of an asset is usually referred to as the return on the price, Equation (9) is re-phrased as

$$R_i^e = -\frac{1}{\eta}\widehat{S}_i \tag{14}$$

where R_i^e refers to the expected return associated with the discovery of oil field i, predicted by the Hotelling model. $\widehat{S}_i$ denotes the change in the resource stock caused by discovery i.

The Reserve Stock

Official reserve estimates as provided by the IEA show that the resource stock has been increasing steadily over time: it has 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 e.g. Hamilton, 2008). Among the various independent assessments of oil reserves, the one by Laherrere and Campbell is known to be the most accurate one (Bentley, 2002). According to their work reserves have been increasing until 1980 and have since declined.[16] Table 2 displays estimated crude oil reserves according

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[16] 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.

to Laherrere (2007). According to these figures, reserves have decreased by 28% in the time period covering 1990-2005.

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.

The quantities discovered in field i are rated against reserve estimates for the corresponding discovery year as shown in Table 2 to obtain the change in reserve stock $\widehat{S}_i$ due to discovery i. See Column (4) in Table 3 for an estimate of discovered quantities and Column (5) of the same table for the resulting change in the reserve stock.

Demand Elasticity

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 estimated values 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 $\eta = 0.05$ for the short run and $\eta = 0.21$ for the long run. Table 6 compares the different studies and results.

For the computation of the expected change in the price of crude oil, an estimate for the short run demand elasticity, $\eta = 0.05$, and one for the long-run demand elasticity, $\eta = 0.26$, is used.

Results on the Predicted Price Decline

Columns (6) and (7) of Table 3 display the socially optimal decline in the price of crude oil to oil field discoveries assuming $\eta = 0.05$ as an estimate of the short-run and $\eta = 0.26$ as long-run elasticity estimate, respectively. Clearly, a higher price elasticity reduces the decline in price that is necessary to sell the additional units on the market.

Accordingly, the expected return ranges between -1.05% and -28.2% for the short-run elasticity estimate ($\eta = 0.05$). It varies between -0.20% and -5.4% for the value of $\eta = 0.26$ assumed as long-run elasticity. The greatest decline should have been observed for Kashagan, the biggest oil field discovered since 1990, resulting in a negative return of -28% assuming the short run elasticity estimate and -5.4% 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.

4.2 Observed Price Decline

In order to make the predicted and the observed price decline comparable, the set of assumptions underlying the derivation of both values needs to be as congruent as possible.

Table 3: Details and Predicted Price Decline for Unanticipated Discoveries

Field Name	Region/Country	Year	URR	$\widehat{S}$	Exp. Return, $R^e_{(\eta=.)}$	
					$\eta = -0.05$	$\eta = -0.26$
(1)	(2)	(3)	(4)	(5)	(6)	(7)
Akpo	West Africa	2000	900	0.1	-1.77	-0.34
Azar	Iran	2005	500	0.06	-1.24	-0.24
Bonga	West Africa	1996	1000	0.11	-2.12	-0.41
Buzzard	North Sea	2001	500	0.06	-1.16	-0.22
Carioca	Brazil	2007	10 000	1.3	-25.97	-5.00
Dalia	West Africa	1997	1 000	0.11	-2.16	-0.42
Erha	West Africa	1990	700	0.07	-1.36	-0.26
Girassol	West Africa	1996	700	0.07	-1.49	-0.29
Gumusut	Malaysia	2004	550	0.07	-1.34	-0.26
Jack	Gulf of Mexico	2006	3000	0.38	-7.59	-1.46
Kashagan	Kazakhstan	2002	12 000	1.4	-28.23	-5.43
Kaskida	Gulf of Mexico	2006	3000	0.38	-7.59	-1.46
Knotty Head	Gulf of Mexico	2005	500	0.06	-1.24	-0.24
Peng Lai	China	2000	500	0.06	-1.14	-0.22
Tahiti	Gulf of Mexico	2002	500	0.06	-1.18	-0.23
Tiber	Gulf of Mexico	2009	500	0.07	-1.32	-0.25
Tupi	Brazil	2007	8 000	1.1	-20.25	-3.89
Ursa	Gulf of Mexico	1995	500	0.05	-1.05	-0.20
Usan	West Africa	2003	500	0.06	-1.20	-0.23
West Seno	Indonesia	1998	600	0.07	-1.32	-0.25

The predicted price decline as given by Equation (10) is the result of a model which assumes zero extraction costs, a constant and iso-elastic demand function, a constant interest rate and, implicitly, also a constant extraction technology. These assumptions need to be translated in a suitable way into the empirical set-up.

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. An analysis of price changes within such a short time horizon reduces the likelihood that any of the factors assumed to be constant in the model have altered significantly. In contrast, changes in the reference rate of risk and changes in supply and demand conditions affect the price of crude oil on a daily basis and need to be accounted for. The observed price decline in Equation (10) is thus proxied by a residual stemming from a regression of the daily crude oil price return on a commodity index and a suitable proxy for the risk free interest rate. In addition to the one-day return, a five-day-average is computed to check the robustness of the results and to investigate the behavior of the return around the event day.

Estimation of the Observed Price Decline

For the estimation of residual returns, a sub-sample is composed consisting of 100 days prior to the announcement plus five days composing the event-window for each discovery announcement. Given that $t = 0$ denotes the actual announcement day, each sub-sample covers the time period $t \in [-102; -2]$ where the event window is given as $t \in [-1; 3]$.

For each sub-sample a risk-adjusted residual return is computed which controls for general market movements and changes in the risk-free interest rate. The following model is estimated for each of the 20 sub-samples:

$$R_t = \alpha_i + \beta_i R_{m,t} + \gamma_i R_{f,t} + e_{i,t} \tag{15}$$

where R_t denotes the return on the crude oil price at day t, i denotes the discovery announcement of field i, R_m is the commodity market index and R_f a proxy of the risk free interest rate. As before, the error term is assumed to follow an AR(1) process with $e_{i,t} = \rho_i e_{i,t-1} + u_t$ where $u_t \sim N(0,1)$. α_i, β_i and γ_i are coefficients and are estimated with the GLS Prais-Winsten procedure (Greene, 2008).

From the residuals of the regression, two measures for the observed price decline are computed. On the one hand, the return over only the next day after a discovery announcement is investigated:

$$\widehat{R}_i^{(1)} = \widehat{e}_{i,t=0} = R_{i,t=0} - \widehat{\alpha}_i - \widehat{\beta}_i R_{m,t=0} - \widehat{\gamma}_i R_{f,t=0} \tag{16}$$

$\widehat{R}_i^{(1)}$ refers to the proxy of the observed return on the price of crude oil on the day of discovery i, denoted as $t = 0$. $\widehat{e}_{i,t=0}$ is the residual and $\widehat{\alpha}_i$, $\widehat{\beta}_i$ and $\widehat{\gamma}_i$ are the estimated coefficients from regression Equation (15).

On the other hand, an average of returns over the five-day event window, spanning one day before the announcement and three days afterwards, is computed:

$$\widehat{R}_i^{(2)} = \frac{1}{5} \sum_{t=-1}^{t=3} \widehat{e}_{i,t} \tag{17}$$

$\widehat{R}_i^{(2)}$ refers to the proxy of the observed return on the price of crude oil after discovery of field i as derived in this first manner.

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.[17] The CRB commodity index by the Commodity Research Bureau is taken as market index, the U.S. federal funds rate as proxy for the risk-free interest rate.[18] All series stem from Datastream and consist of end-of-the-day (settlement) prices.

Result

Columns (1) and (2) of Table 7 in the Appendix display the results for the observed price decline. The one-day returns $\widehat{R}_i^{(1)}$ range from -4.46% to 3.89%. The five-day average returns $\widehat{R}_i^{(2)}$ range from -1.27% to 2.44%. A closer investigation of the behavior of the fields individually is provided in the next section.

Figure 3 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 90%- standard error bands.[19] Table 4 displays the corresponding mean. Accordingly, the price of crude oil declines, on average, on days of discovery announcements, $t = 0$, by $\bar{R}^{(1)} = 0.88\%$. On subsequent days, the return is not significantly different from zero.

The average of the five-day average return across the 20 announcements, $\bar{R}^{(2)} = \frac{1}{20}\sum_{i=1}^{20}\widehat{R}_i^{(2)}$, is only slightly negative (-0.01%). Thus, the decrease in the price of crude oil following the discovery announcement is neutralized within the event window.[20] This result highlights that the market adjusts relatively fast to the news of a change in resource scarcity.

The next section quantifies the difference between the socially optimal and the observed price decline.

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[17] Note that, according to the model, the price of crude oil is expected to adjust to the change in the opportunity cost of resource use across all maturitities. This stands in contrast to a change in the price of crude oil of only far-maturing futures contracts. The latter simply serves as a sign that expectations regarding future supply conditions have changed.

[18] Note that the interest rate, $R_{f,t}$, is defined as the absolute change in the federal funds rate. $R_{m,t}$ is the percentage change in the price of the commodity price index, i.e. $R_{m,t} = \frac{P_{m,t}-P_{m,t-1}}{P_{m,t-1}}$ where $P_{m,t}$ is the end-of-the-day settlement price of the commodity price index.

[19] The confidence interval is computed as $CI_t = \bar{R}_t \pm t_{\alpha/2;(n-K)}\frac{s}{\sqrt{n-K}}$

[20] Earlier versions of this paper applied the event study methodology to determine whether an abnormal return takes place after discovery announcements. The event window was defined as $t \in [-1; 3]$ and no significant decline could be detected for this time frame. This result is equivalent to the finding here that the risk-adjusted average return, $\bar{R}^{(2)}$, is not significantly different from zero.

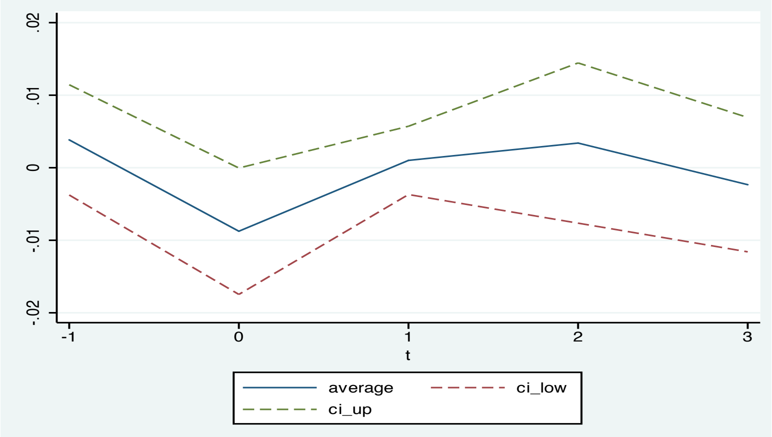

Figure 3: Residual Return during Event Window

Table 4: Average Return (in %) during Event Window

Day	$t=-1$	$t=0$	$t=1$	$t=2$	$t=3$
$\bar{R}_t$	0.66	-0.88	-0.25	0.38	0.08

4.3 Is the Adjustment in Line With the Hotelling Model?

This section aims at comparing the observed decline in the price of crude oil with the predicted decline as computed from the Hotelling model. The adjustment parameter, $\widehat{\theta}_i$ - given as the ratio of observed to expected price decline for each discovery, i - measures the degree of adjustment to the socially optimal solution. It is clear that values for $\widehat{\theta}_i$ closer to one indicate an adjustment which is more in line with the social optimum whereas negative values indicate that the observed price increased contrary to expectations. Figure 4 illustrates the idea of $\widehat{\theta}_i$.

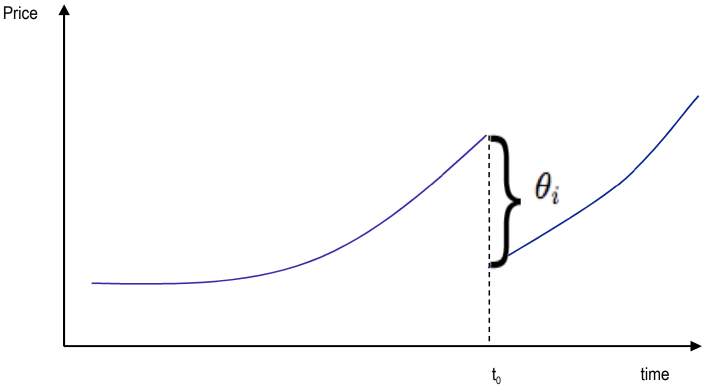

Figure 4: Determining the distance from the optimal solution

The deviation of observed values from the socially optimal solution is computed for each field, i, based on the one-day risk adjusted return, $R_i^{(1)}$, only. A value of $\widehat{\theta}_i$ is computed for both, the short- and long-run demand elasticity estimate. The adjustment parameter is given as:

$$\widehat{\theta}_i^s = \frac{\widehat{R}_i^{(1)}}{R_{i,\eta=0.05}^e} \tag{18}$$

and

$$\widehat{\theta}_i^l = \frac{\widehat{R}_i^{(1)}}{R_{i,\eta=0.26}^e}. \tag{19}$$

In addition to the summary statistics, a hypothesis test is conducted for both types of adjustment parameters. The null hypothesis states that the average adjustment is equal to one. This indicates that the observed crude oil price decline is not significantly different from its predicted decline. The null hypothesis and the alternative are given as:[21]

$$H_0 : \bar{\theta} = 1 \tag{21}$$

$$H_A : \bar{\theta} \neq 1. \tag{22}$$

where $\bar{\theta} = \frac{1}{20}\sum_{i=1}^{20} \theta_i$ is the average of the adjustment parameters (computed for the long- and short-run estimate of demand elasticity, respectively).

Table 5: Summary Statistic for Adjustment Parameters

Adjustment parameter	$\widehat{\theta}_i^s$	$\widehat{\theta}_i^l$
mean	0.53	2.24
sd	1.07	4.48
t-statistic	-1.93	1.20

Table 5 shows that the average adjustment for the estimate based on the short-run elasticity ($\eta = 0.05$) is 0.53. Thus, the actual price decline is on average almost half as large as the predicted price decline. The average adjustment based on the long run elasticity estimate ($\eta = 0.26$) is 2.24 which indicates that observed returns are much higher than the ones expected to be observed. The variation of $\widehat{\theta}$ decreases with demand

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[21] The test-statistic is computed as

$$t = \frac{\bar{\theta} - 1}{s/\sqrt{n-K}} \tag{20}$$

where s is the sample standard deviation, $n = 20$ and $K = 2$. The critical value, $t_{\alpha/2}(n-K)$, corresponding to the 95% confidence interval is given as 2.093.

inelasticity: smaller values of the demand elasticity result in a much smaller variation of $\widehat{\theta}$ than larger ones. The null hypothesis that the adjustment parameter is equal to one cannot be rejected for either elasticity estimate. Both values of the t-statistic are smaller than 2.093 (95% confidence level). Thus, the adjustment of the observed price decline is sufficiently close to its predicted value.

Figure 5 plots the adjustment for each field, i. The straight line indicates the socially optimal price decline (i.e. $\theta = 1$). Only the announcements of two fields- Akpo and Azar - are associated with returns on the price of crude oil which are counter-intuitive. The announcements of all other fields are associated with a negative return.

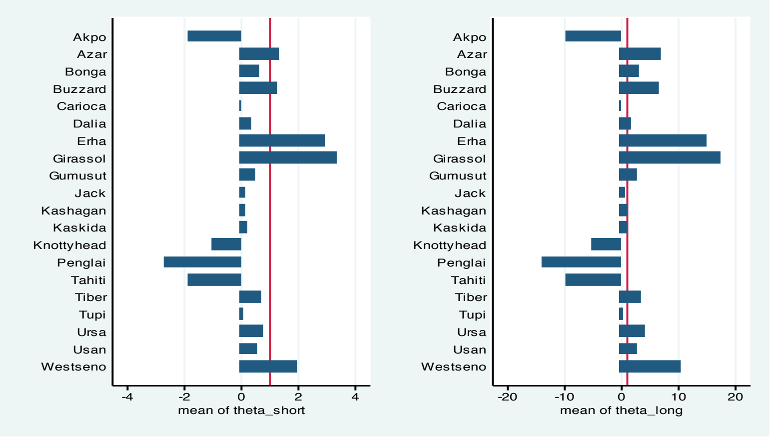

Figure 5: Deviations from Expected Behavior

5 Conclusion

The existence of an opportunity cost of resource use in the price of a non-renewable resource distinguishes the price formation of a non-renewable resource from that of a renewable resource. It is thus a necessary prerequisite for the Hotelling rule to hold (Hotelling, 1931). This paper has focussed on providing evidence for the existence of this price component.

A test on the presence of the opportunity cost component in the price of a non-renewable resource can be conducted on the ground that changes in the scarcity of the resource should alter the price of it. Unanticipated discoveries of additional reserve reservoirs, such as crude oil field discoveries, provide an ideal example for an unexpected change in scarcity. If total resource availability is indeed a component in the price of crude oil, it should adjust to the news of oil field discoveries (Dasgupta & Heal, 1979).

The test has involved four steps: First, the simple Hotelling model is used to illustrate the interdependence of the price and the stock size. It served 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 quantified.

We observe for the average of all unanticipated discoveries a price decline of -0.88% following discovery announcements. This decline is significantly different from zero considering a 90% confidence interval. The average of the five-day average return across the 20 announcements, in contrast, is not significant. It indicates that the market adjusts relatively fast to news on changed resource scarcity and suggests the study of high-frequency data to isolate the price effect of such announcements even more precisely.

The size of the price adjustment caused by discovery announcements is not inconsistent with the price decline expected in a social optimum: for a relatively high and a relative low estimate of the demand elasticity the adjustment parameters do not differ significantly from the situation of a perfect adjustment. For a very low value of the demand elasticity (short-run estimate), the market price adjusts on average by 52%. Using a higher value of the demand elasticity (long-run estimate), the market price even overshoots the socially optimal solution (224%). Clearly, the deviation from the socially optimal solution varies with the choice of the demand elasticity parameter.

All in all, this study finds some evidence to believe that the price of crude oil indeed adjusts to news about changes of its resource availability. This result indicates that the price of crude oil contains a component which reflects the scarcity of the resource - a necessary pre-requisite for the Hotelling rule to hold.

6 Appendix

6.1 Overview of Demand Elasticities in the Literature

Table 6: Literature Results on Price Elasticity of Demand

Name	Sample Size	Method	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

6.2 Expected versus Observed Decline in the Price of Crude Oil

Table 7: Observed Decline in the Price of Crude Oil

Field Name	Obs. Return, $\widehat{R}_i^{(\cdot)}$	
	$\widehat{R}_i^{(1)}$	$\widehat{R}_i^{(2)}$
	(1)	(2)
Akpo	3.39	2.44
Azar	1.54	0.69
Bonga	-1.91	0.84
Buzzard	-1.46	0.77
Carioca	0.39	0.55
Dalia	-0.22	-0.63
Erha	-0.30	-0.88
Girassol	-4.46	0.09
Gumusut	-1.97	0.09
Jack	-2.12	-1.10
Kashagan	-0.74	-0.75
Kaskida	-1.61	-0.89
Knotty Head	-2.56	0.00
Peng Lai	-0.18	-0.90
Tahiti	-0.92	-0.88
Tiber	-1.02	0.58
Tupi	-0.33	0.74
Ursa	-0.25	0.22
Usan	-0.74	-1.27
West Seno	-2.07	0.25

Columns (1) and (2) display the observed risk-adjusted one-day return and the risk-adjusted five-day average return, respectively.

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