Valuation of Crude Oil and Gas Reserves

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Abstract
The valuation of crude oil and gas reserves is a critical step in pricing crude oil and gas producing firms. This is of interest both to academics and practitioners who are called upon to value these firms. It is also of interest to regulators, particularly in their oversight of mergers and acquisitions and the issues of securities to the public. Our results reject the notion that the market value of crude oil and gas per unit of reserves varies one-to-one with the current price, net of extraction costs (Hotelling model). Crude oil and gas reserve pricing appears is more complex in practise with both production rate and the proportion of developed proven reserves playing a role in valuation. We use fixed effects panel methods in analysis of data provided by IHS Herold Inc, which comprises 409 crude oil and gas producers (3303 firm-years) over an 18-year period from 1992 to 2008. We find no evidence to support the Hotelling model prediction of a one-to-one relation between the market value of crude oil per unit of reserves and the price of these reserves, net of extraction costs. There is evidence of time variation in this pricing relationship, with the relation being correlated with extraction rate. Further, there is evidence that the proportion of proven reserves that are developed is positively correlated with the market value of reserves. The main implication to be drawn from this study is that the valuation of crude oil and gas reserves requires more information than just reserve volume and spot price.

Keywords: crude oil pricing, Hotelling model, Adelman model.

JEL Codes: G14

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The valuation of a crude oil and gas producer is a complex task and, given discounted cash flow methods, perhaps the most difficult task is the valuation of the reserves. Both practitioners and academics are often called upon to value the reserves held by crude oil and gas producers and yet there is some contention about the most appropriate valuation method to use. While discounted cash flow analysis is commonly used in the valuation of these firms, it has been suggested that the reserves could be valued by simply taking the product of the reserve volume and current spot price, net of extraction costs (Hotelling (1931); Miller and Upton (1985a)). The simplicity of the this approach, which suggests a one-to-one relation between market value per unit of reserve and the crude oil price, net of extraction costs, has attracted some empirical support (Grain and Jamal (1991); Miller and Upton (1985a); Miller and Upton (1985b)). It has also proven useful as a simplifying assumption in the valuation of commodity producers where real option effects are material (BRENNAN and SCHWATZ paper). Yet, this application of the Hotelling’s work has been questioned both by practitioners and academics, with recent research suggesting a more complex relationship explained in terms of production and regulatory constraints (Adelman (1990); Davis and Cairns (1998); Davis and Cairns (1999); Davis and Moore (1998); Krautkraemer (1998); Thompson (1996); Thompson (2001); Watkins (1992 )). In particular, it is argued the relation between the market value of reserves and the underlying commodity price may not be stable over time, changing with discount rate and production rate (Adelman (1990 )).

We test the Hotelling model using crude oil and natural gas information obtained from gas producers included in the IHS Herold Inc. data set covering a period from 1992 to 2008. We use unbalanced fixed effects panel analysis of data drawn from a maximum of 409 oil and gas producers (3303 firm-year observations) that traded at some time over the 18-year period. Various filters (2%, 5% and 10%) are imposed on the data to assess the impact of extreme values on the analysis, with results from analysis of the 5% filtered data reported here. Regardless of filter choice, we find no evidence to support the simple Hotelling prediction of a one-to-one relation between the market value of crude oil per unit of reserves and the price of these reserves, net of extraction cost.
Further, we find that while estimated production rate has explanatory power over the market value of producer crude oil reserves, our proxy for producer discount rate does not support the Adelman model. The results could be explained by measurement error, particularly in the separation of crude oil and gas production (upstream) and other activities (downstream) yet robustness tests do not support this alternative explanation. Regulation could have a role to play in this result. Both the USA and Canada heavily regulate their producers, particularly in terms of setting out the drilling and pumping activity that is to take place. If this regulation were to bias estimated coefficients away from the optimal Hotelling results then there would be differences between producers based solely in USA or Canada and those based elsewhere in the world. We also explore this possibility though there is no evidence of a statistically significant difference between these two groups of producers. Finally, there is little discussion concerning the impact of the proven reserve development on the ability of producers to extract crude oil and gas. We find evidence that the proportion of developed proven reserves that a producer holds has a part to play in explaining variation in the value of reserves.

The discussion provided in the following section gives some insight into the literature and this leads to the hypotheses developed in Section II. Data is described in Section III and the results of analysis are reported in Section IV. Conclusions are reported in Section V.

I. Background

Hotelling’s initial model is extended and tested by Miller and Upton (Hotelling (1931); Miller and Upton (1985a )) though the results from this work have generated considerable discussion. Perhaps the most intriguing research comes from the work of Adelman (1990), who develops a model focusing on the nature of the crude oil extraction process as it takes place in practise, with particular attention devoted to identifying the total reserves available for exploitation and the impact of physical constraints and regulation on production levels. The Miller and Upton derivation of the Hotelling model is summarised in the next sub-section, while following sub-sections focus on questions that have arisen concerning this approach.
A. Miller and Upton studies

Hotelling shows that under certain conditions exhaustible natural resource prices increase over time at the rate of interest (Hotelling (1931)) and while there is a range of testable implications arising from this model, support for many of its key predications have not been forthcoming (Krautkraemer (1998)). Nevertheless, the valuation of crude oil producing companies is of particular interest to both academics and practitioners and so it is not surprising that the application of the Hotelling model to the valuation of crude oil and gas reserves by Miller and Upton attracted considerable attention. Following Miller and Upton’s derivation it is possible to show that in equilibrium (see Appendix):

\[
\frac{V_0}{R_0} = (1 - \tau)(p_0 - C_{q_0}) - K_1 - K_2
\]

where:
- \( V_0 \) = value of the firm at time 0
- \( R_0 \) = reserves at time 0
- \( \tau \) = corporate tax rate for the producer
- \( p_0 \) = crude oil price at time 0
- \( C_{q_0} = \frac{\partial C_0}{\partial q_0} \) = the first derivative of the extraction cost with respect to quantity produced, or marginal cost, at time 0
- \( C_{Q_t} = \frac{\partial C_t}{\partial Q_t} \) = the first derivative of the cost function with respect to cumulative production at time \( t \)

\[
K_1 = \frac{1}{R_0} \sum_{t=0}^{N} \frac{F_t(1 - \tau)}{(1 + r)^t}
\]

\[
K_2 = \frac{1}{R_0} \sum_{t=1}^{N} q_t \sum_{s=0}^{t-1} \frac{C_{Q_s}(1 - \tau)}{(1 + r)^s}
\]

\[
F_t = C_t(q_t, Q_t) - C_{q_t} q_t = \text{the difference between average and marginal cost at time } t
\]

Miller and Upton regress the market value per unit of reserves on current price, net of extraction costs. They rely on oil and gas data drawn from two sample periods, December 1979 to August 1981 and August 1981 to December 1983 (Miller and Upton (1985a); Miller and Upton (1985b)). On the assumption that the tax rate, \( \tau \), and the constants, \( K_1 \) and \( K_2 \), are zero, the regression model that they estimate takes the form:
\[ \frac{V_0^i}{K_0^i} = \alpha + \beta (\rho_0^i - c_0^i) \]  

where \( V_0^i \) is the current market value of the oil and gas reserves for firm \( i \) at time \( t \),
\( K_0^i \) is the total recoverable reserves of the oil and gas for firm \( i \) at time \( t \),
\( \rho_0^i \) is the current market price of oil and gas for firm \( i \) at time \( t \),
\( c_0^i \) is the current extraction (uplift) cost for oil and gas for firm \( i \) at time \( t \).

In this restricted form, if the Miller and Upton model holds then the intercept has a value of zero and the slope term a value of one. Miller and Upton argue that the intercept in equation (2) could vary with cost function. As shown in equation (1), the value of the project is also a function of the difference that exists between marginal and average cost as well as cumulative production (Miller and Upton (1985a)). It is argued that both of these terms are uncorrelated with the current net crude oil price and so the intercept captures the residual from these two effects. It is also suggested that the slope term may be somewhat less than one to reflect the impact of taxes, as per equation (1), though Miller and Upton propose that producers can arrange their affairs so that taxes have little impact on their value.

Miller and Upton use data drawn from the Oil Industry Comparative Appraisals published by HIS Herold Inc. While regression based tests support the model in the first sub-period, December 1979 to August 1981 (Miller and Upton (1985a)), the results for the second sub-period, August 1981 to December 1983 (Miller and Upton (1985b)), are less convincing. It is argued that the lack of variation in the crude oil prices in the second period along with measurement error may have resulted in less precise estimates in the second period. In the second of their studies, Miller and Upton also analyse a group of 12 royalty trusts that focus on crude oil reserves because it is argued that the simple structure of these trusts minimises errors in measuring the market value of reserves. The results from this analysis support the Hotelling model, though Miller and Upton do acknowledge the small size of the sample.
B. Taxes

Miller and Upton state that if market value reflects after corporate tax values then the relation between the market value per unit of reserves and the price after extraction costs reflects the impact of corporate tax. Indeed, the slope coefficient in equation (1) takes on the value \((1 - \tau)\) as per equation (1), but Miller and Upton note the plethora of deductions that could be used to reduce tax liabilities and so, with some careful management, the marginal tax rate for a crude oil producer could be reduced to something quite close to zero. Miller and Upton note that the offset for depletion has an important impact on the behaviour of producers who face a tax system similar to that in the USA (Miller and Upton (1985a)). The depletion offset allows for a tax deduction based on the original purchase cost of the reserve where the producer is allowed to write off the original cost of the reserve in a similar way to the depreciation of plant and equipment.\(^1\) It is also common for producers to set off intangible drilling costs for new wells against taxable income.\(^2\) As a result, Miller and Upton argue that the slope coefficient estimated in equation (2) would lie somewhere in the range, \((1 - \tau) \leq \beta \leq 1\). The lower bound reflects the full tax situation where the offsets cannot be used, \(\beta = (1 - \tau)\) and the upper bound takes effect where the offsets completely exhaust the corporate tax liability so that \(\beta = 1\). With the introduction of taxes, the basic Hotelling relation is written as:

\[
\frac{V_0^{it}}{K_0^{it}} = \alpha + \beta(p_0^{it} - c_0^{it})(1 - \tau)
\]  

(3)

C. Fixed reserves

The two Miller and Upton pooled cross-sectional studies use three-years of data and implicitly assume the existence of a fixed reserve of an exhaustible natural resource that is held by each of the firms in the sample. This may not be a reasonable proposition over a longer period of time with improved extraction technology and the discovery of new reserves (Krautkraemer (1998)). The

\(^1\) A problem with this offset arises where reserves are subsequently found to be larger than expected or if prices increased substantially. In these situations it becomes tax effective to sell the reserves or spin them off into royalty trusts. Master limited partnerships have also been used for this purpose (Grain and Jamal (1991)).

\(^2\) There are a number of other specific tax breaks offered to USA crude oil and gas producers (Miller and Upton (1985a)) and many of these remain in effect as at the end of the sample period, 2008.
problem with the assumption of fixed and known reserves is particularly apparent in the Figure 1
where total year-end reserves reported by the firms included in this study, expressed in barrel
equivalents, are fairly stable from 1992 to 2004. The reported reserves actually increase from 2005
to 2008, with a considerable shift in the composition of the stated reserves from gas to crude oil
from 2003 through to the end of 2008. While the ultimate reserves might be guessed at, it does not
appear that the exact quantum of crude oil and natural gas reserves existing within the earth’s crust
is currently know with much precision.

[Insert Figure 1 about here]

D. Constraints on production

Miller and Upton implicitly assume that producers have complete discretion in their ability
to maintain production levels that are optimal in an economic sense. Yet, in the crude oil extraction
industry, production appears to be governed by physical constraints associated with bringing the oil
to the surface (Adelman (1990)). Put simply, the greater the pressure in the reserve the less costly
the process of extracting the crude oil. There are also regulatory constraints that affect the ability of
firms to extract crude oil in the most economically efficiently way (McDonald (1994)). Thus, the
optimal level of production may not be achievable in practice.

Adelman models total reserves, $R_0$, as the sum of production over the life of the reserve
(from period $0$ to $T$) with initial production quantity per unit of time, $Q_0$, declining exponentially at
the rate $a$ to give $R_0 = Q_0 \int_{t=0}^{T} e^{-at} \, dt$ (Adelman (1990)). As time, $T$, approaches infinity this
relationship can be integrated to give $R_0 = Q_0 / a$. The net price received over the life of the project
is assumed constant $(p_0 - c_0)$. The discount rate is set to $r^*$.

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3 This differs from the Hotelling model, which predicts that prices rise at the rate of interest.
In a competitive market the value of the reserve is a function of the price net of extraction costs, the quantity of crude oil produced at time $t$ $(Q_0e^{-at})$ and the projected capital expenditures expected to occur over the life of the mine $(KQ_0)$.

$$NPV = \int_{t=0}^{T}(p_0 - c_0)e^{-r^*t}Q_0e^{-at} dt - KQ_0$$

$$= (p_0 - c_0)Q_0 \int_{t=0}^{T} e^{-(a+r^*)t} dt - KQ_0$$

(4)

As time, $T$, approaches infinity, the value of the reserves is written as follows:

$$V = (p_0 - c_0)R_0 - kaQ_0 = (p_0 - c_0)Q_0/(a + r^*) - kaQ_0.$$  

(5)

Given the limit of total production $Q_0 = R_0a$, this can be rewritten as:

$$V = R_0 \frac{a}{(a + r^*)}(p_0 - c_0) - kaQ_0$$

$$\frac{V}{R_0} = \frac{a}{(a + r^*)}(p_0 - c_0) - \frac{kaQ_0}{R_0}$$

(6)

Thus, if the Adelman proposition holds then the regression that Miller and Upton fitted to their data will take the form:

$$\frac{V_0}{R_0} = \frac{a}{a + r^*}(p_0 - c_0) - K$$

(7)

Adelman argues that $a$ and $r^*$ have been approximately equal in the past and so a regression fitting equation (2) to the data would generate a slope term, or $\beta$ coefficient close to 0.5 along with a negative intercept that captures the capital cost of further developing the reserve (Adelman (1990)). While Adelman questions the Miller and Upton result, it could be argued that the Adelman approach also takes a rather extreme view on production flexibility, assuming that the producer maintains the maximum feasible rate of extraction at all times. The assumption of fixed price net of extraction costs is critical to the Adelman result. Indeed, if we allow price, net of extraction costs, to increase at the discount rate in line with the Hotelling model prediction then the discount rate, $r^*$, drops out of the Adelman model leaving the Hotelling result, with $\beta = 1$:

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4 Thompson proposes a slightly different model, which allows for different rates of change in marginal costs and prices over the life of the reserve. The Miller and Upton prediction is maintained while these growth rates equal zero, though this is not true where one (or both) of the rates is unequal to zero (Thompson (2001)).
\[
\frac{V_0}{R_0} = \frac{a}{a} (\rho_0 - c_0) - K = \beta (\rho_0 - c_0) - K
\]

**E. Regulation**

Much of the literature ignores regulation though this may be one of the more important features of USA and Canadian based crude oil production. Both crude oil well spacing and crude oil extraction rates have been regulated since the 1930s in the USA and this form of regulation has been replicated in Canada (McDonald (1994)). McDonald notes that Hotelling specifically excluded crude oil production from his initial discussion because of the problem of “… rivalrous extraction of a fugitive resource from a common pool …” (McDonald, 1994, p.7). Under the North American regulations, operators developing a new reserve must apply for a spacing order for the reserve. This lays out a plan for uniformly spaced wells that cover the entire reserve. Within this regulatory environment, there is incentive for crude oil extraction to occur at the lesser of the achievable extraction rate and the regulated extraction rate. If one producer chooses to reduce its rate of extraction, the other producers who work the same reserve immediately take up the unused extraction allocation. McDonald suggests that the Adelman model with initial production rate adjusted for a constant decline in extraction may better capture actual production decisions that are subject to the binding regulation found in the USA and Canada. It appears that regulatory constraints could restrict producers from achieving production levels that are optimal in an economic sense (McDonald (1994)).

**F. Subsequent empirical tests**

There are a number of tests of the Miller and Upton proposition with little support for the simple Hotelling prediction that the value per unit of reserves is the current price of crude oil and gas net of extraction costs. One of the few supporting studies is that of Grain & Jamal, who replicate the Miller and Upton analysis using a sample of 91 royalty trusts and master limited partnerships over the period from 1981 to 1986 (Grain and Jamal (1991)). It is argued that due to tax law these entities are much simpler to analyse than the corporate entities used in the Miller and
Upton analysis. For example, there is little evidence of non-petroleum assets in royalty trusts, which can be difficult to value, and the few liabilities that are reported by these entities are relatively simple to value. This simplification reduces measurement error in reserve valuation. Their data is obtained from each entity’s 10K report and the results support the Hotelling model prediction (Miller and Upton (1985a)), with a β coefficient that is positive and not statistically significantly different from one.

Much of the recent literature concentrates on the traded value of reserves, following the recommendation of Miller and Upton who state that “… the ideal measure (of the value of reserves) would be actual transaction prices for fields.” (Miller and Upton, 1985b Journal of Political Economy, p.15). While there was not sufficient data from this market for use in the original Miller and Upton studies, reserve sale information is used in more recent studies (Adelman and Watkins (1995); Watkins (1992)).

Watkins compares the aggregate reserve sale price with the current net price of the oil and gas identified within the reserves (Watkins (1992)). On estimating equation (10) Watkins obtains an estimated slope coefficient of 0.54, which is closer to the Adelman model prediction of 0.50 than the Hotelling model prediction of somewhat less than 1.00. Watkins notes that reserves are continually changing with exploration and development of existing and new areas, so much so that it is rarely feasible, ex ante, to identify the total in-ground reserves that will be depleted over time. Davis and Cairns further explore the importance of physical and regulatory limits on oil production (Davis and Cairns (1998); Davis and Cairns (1999); Davis and Moore (1998)) with a focus on modelling the impact of uncertainty and production constraints. They find support for the work of McDonald (1994) and Adelman (1990), arguing that producers who face binding production constraints, either because of the nature of the extraction process or because of regulatory restrictions, may not be able to achieve optimal production levels in practice. Davis and Cairns argue that, at best, the Hotelling model provides an upper limit on the value of reserves after

\[ \text{Dependent variable measurement error in regressions results in increased standard errors and lower statistical significance.} \]

\[ \text{This has implications for tests of the Hotelling model because it removes the direct link between net prices in different periods over the life of the reserve. Producers still equate marginal cost with marginal revenue in each period but the maximum production constraint no longer holds.} \]
adjustment for uncertainty, binding production constraints and/or binding regulatory constraints (Davis and Cairns (1998); Davis and Cairns (1999); Davis and Moore (1998)).

II. Hypotheses

The first hypothesis that we test concerns the question of whether the Hotelling result applies to the valuation of crude oil reserves. If the Miller and Upton argument is appropriate then the market value per unit of reserves will vary one-to-one with the price net of extraction costs. If the Adelman argument applies then the relation between reserve market value and crude oil price net of extraction costs is a function of discount rate and production rate for the producer. Given historical data, the slope is expected to take a value approximately equal to 0.5 around the 1980s though both discount rate and extraction rate will tend to change over time and so the estimated value of this coefficient may change over time.

Hypothesis 1

H0: There is no relation between market value of reserves and crude oil price net of extraction costs.
H1a: There is a one to one relation between market value per unit of reserves and price net of extraction costs, \( \beta = 1 \), in equation (2).
H1b: The relation between the market value of reserves and the price net of extraction costs is a function of the discount rate and extraction rate, \( \beta = f(r^*, a) \), in equation (2).

If a Taylor series approximation is taken for the function \( f(r^*, a) \) then the slope coefficient can be written as a function of the discount rate \( (r^*) \) and the rate of decline in extraction \( (a) \) or, at the limit, the ratio of production for the period to reserves existing at the end of the period. Thus:

\[
\beta = \phi_1 + \phi_2 r^*_it + \phi_3 a_{it} \tag{8}
\]

Substituting this into equation (2) gives:

\[
\frac{V^d_{it}}{K^d_0} = \alpha_i + \alpha_t + (\phi_1 + \phi_2 r^*_it + \phi_3 a_{it}) \left( \rho^d_{it} - c^d_{it} \right) + \epsilon_{id} \tag{9}
\]

and rearranging equation (9) gives:

\[
\frac{V^d_{it}}{K^d_0} = \alpha_i + \alpha_t + \phi_1 \left( \rho^d_{it} - c^d_{it} \right) + \phi_2 r^*_it \left( \rho^d_{it} - c^d_{it} \right) + \phi_3 a_{it} \left( \rho^d_{it} - c^d_{it} \right) + \epsilon_{id} \tag{10}
\]
This model includes two interaction terms to capture the impact of the Adelman predictions concerning discount rate and production rate, \( r^*_{it} \left( p^0_{0it} - c^0_0 \right) \) and \( \alpha^*_{it} \left( p^0_{0it} - c^0_0 \right) \). Thus, a test of hypothesis 1 involves a joint test of the coefficients estimated for these interaction terms and takes the form, \( \phi_2 = \phi_3 = 0 \) if the Hotelling model is to apply. The basic test of the Hotelling model is also undertaken by testing for \( \phi_1 = 1 \).

The question of taxes is generally ignored in empirical research and while Miller and Upton discuss the impact of taxes they reason that there will be little tax impact because crude oil producers organise their affairs to minimise the impact of taxes. If taxes are important then model fit should improve and tax adjusted net price should better explain the variation in the market value per unit of reserves. We use effective tax rate as an approximation for producer marginal tax rate. This leads to the second hypothesis.

**Hypothesis 2**

H0: There is no relation between market value of reserves and crude oil price net of extraction costs and taxes.

H1a. There is a one-to-one relation between market value per unit of reserves and price, net of extraction costs and taxes.

H1b. The relation between the market value of reserves and the price net of extraction costs and taxes is a function of the discount rate and production rate.

The model defined in equation (10) is used to test the importance of producer-specific taxes on the sensitivity of the market value per unit of reserves to changes in crude oil price net of extraction costs and taxes \( \left( p^0_{0it} - c^0_0 \right) (1 - \tau_{it}) \).

\[
\frac{V^0_{0it}}{R^0_{0it}} = \alpha_i + \alpha_t + \phi_1 \left( p^0_{0it} - c^0_0 \right) (1 - \tau_d) + \phi_2 r^*_{it} \left( p^0_{0it} - c^0_0 \right) (1 - \tau_{it}) + \phi_3 \alpha^*_{it} \left( p^0_{0it} - c^0_0 \right) (1 - \tau_{it}) + \epsilon_{it}
\]

\( (11) \)

The two interaction terms that capture the impact of the Adelman predictions are now \( r^*_{it} \left( p^0_{0it} - c^0_0 \right) (1 - \tau_{it}) \) and \( \alpha^*_{it} \left( p^0_{0it} - c^0_0 \right) (1 - \tau_{it}) \), and the test of hypothesis 2 involves a joint test of the coefficients estimated for these interaction terms and takes the form, \( \phi'_2 = \phi'_3 = 0 \) if the
Hotelling model is to apply. Again, a basic test of the Hotelling model is also undertaken by testing for $\phi_1 = 1$.

Regulation in the USA and Canada restricts well spacing and extraction rates and this could constrain crude oil producers from achieving economic optimum production levels. This level of regulation is not evident in the Asia-Pacific region, for example, and so it is expected that if regulation constrains production decisions then there will be a difference in the slope coefficient, $\beta_i$, estimated for the crude oil producers that operate in the USA and Canada compared with those that operate in other regions of the world.

**Hypothesis 3**

H0: The relation between the market value of reserves and price net of extraction costs is independent of country regulation of the crude industry.

H1: Due to constraints arising from US and Canadian regulation the sensitivity of the market value of reserves to crude oil price, net of extraction costs, is greater for producers operating outside the USA and Canada ($\phi_{1,USA,Canada} < \phi_{1,elsewhere} \leq 1$).

This hypothesis is tested using a test for structural change between the model fitted to those producers that operate mainly in the USA and Canada, compared with producers that do not concentrate their production in these two countries. The final hypothesis is concerned with the development of the reserves held by the crude oil and gas producer.

**Hypothesis 4**

H0: The proportion of developed proven reserves to total reserves is not correlated with market value of reserves.

H1: The proportion of developed proven reserves to total reserves is positively correlated with market value of reserves.

This hypothesis extends on the arguments of Adelman and McDonald where producers are constrained by physical production constraints or regulation. It is possible that the level of development of the reserves controlled by the firm will have an impact on and the ability of the producer to extract crude oil and gas from the reserve and so this will have an impact on the value of the reserves that the producer holds. All else held constant, the greater the level of the reserves that are developed the greater the value of the reserves.
III. Data

Variables used in analysis are obtained from a number of sources. The reserve data and estimates of extraction costs (lifting costs) are obtained from IHS Herold Inc.\(^7\) Book value of debt and the book value of activities excluding the extraction of the crude oil and gas (non-upstream) elements of the firm are obtained from IHS Herold Inc., the SEC through the Edgar system\(^8\), OSIRIS\(^9\) and Compustat.\(^10\) Crude oil producer share price and number of shares outstanding are obtained from Compustat and from IHS Herold Inc., though the IHS Herold Inc. data is used where data is not available from Compustat.\(^11\) The closest to maturity futures price is used as a proxy for the current price of crude oil and natural gas and this is obtained from CRB.\(^12\) The natural gas price is initially expressed in terms of British thermal units and this is adjusted to barrel of oil equivalent.\(^13\) Currency based data are expressed in USDs. Finally, USA consumer price index numbers are obtained from St Louis Federal Reserve.\(^14\)

The variable, \(\frac{V_0^i}{R_0^i}\), is the ratio of the market value of the upstream assets of the firm divided by the total reserves controlled by the producer. The reserves, \(R_0^i\), expressed in barrel of oil equivalent, includes proven reserves of oil/liquids and gas, both developed and undeveloped, as reported at year-end. Gas reserves are expressed in terms of billion cubic feet and this is converted to barrel of oil equivalent from using the conversion rate of 6 thousand cubic feet to a barrel of oil, consistent with the conversion rate used by IHS Herold Inc. The market value of the reserves controlled by the producer (upstream assets), \(V_0^i\), is calculated by deducting the book value of assets associated with activities other than the extraction of crude oil and gas (downstream assets) from the market value of the firm. The market value of the firm is approximated by the sum of the

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\(^7\) [http://www.herold.com/research/herold.home](http://www.herold.com/research/herold.home)

\(^8\) The EDGAR Database of Online Corporate Financial Information provided by the U.S. Securities and Exchange Commission ([http://www.sec.gov/edgar.shtml](http://www.sec.gov/edgar.shtml)).

\(^9\) OSIRIS is a database of listed firms from around the world supplied by Bureau Van Dijk ([http://www.bvdinfo.com/Products/Company-Information/International/Osiris.aspx](http://www.bvdinfo.com/Products/Company-Information/International/Osiris.aspx)).

\(^10\) [http://www.compustat.com/academic/](http://www.compustat.com/academic/)

\(^11\) The IHS Herold Inc. data is generally used where the crude oil producer is not listed on USA stock exchanges or does not have an ADR traded on USA stock exchanges.

\(^12\) [http://www.crbrtrader.com/datacenter.asp](http://www.crbrtrader.com/datacenter.asp)

\(^13\) [http://www.spe.org/industry/reference/unit_conversions.php](http://www.spe.org/industry/reference/unit_conversions.php).

\(^14\) The consumer price index (CPIAUCNS) for all urban consumers: all items (not seasonally adjusted) is used for adjustment for change in price levels ([http://research.stlouisfed.org/fred2/](http://research.stlouisfed.org/fred2/)).
market value of equity capital, total long-term debt, total short-term debt and accounts payable. The
time series of values for each producer is then restated in terms of 2008 dollars using the series,
Consumer Price Index for All Urban Consumers: All Items, obtained from the U.S. Department of

The price net of extraction costs, $p_{0i}^H - c_{0i}^H$, is calculated for each year for each firm where
data is available. The spot price for both gas and crude oil, $p_{0i}^H$, is estimated using the closest to
maturity futures contract price. The NYMEX contract written on WTI crude oil provides an
estimate of crude oil price and the NYMEX contract written on the Henry Hub natural gas,
expressed in barrel of oil equivalent, is used for our estimate of the natural gas price. The uplift
cost (cost of extraction), $c_{0i}^H$, is obtained from IHS Herold Inc. and this covers all costs of upstream
production including production expenses, shipping/transport/handling expenses, taxes other than
income taxes and production related general and administrative costs. The net price is expressed in
terms of 2008 dollars using the CPI described above. The effective tax rate, used in calculation of
the tax adjusted net price, is based on the IHS Herold Inc. effective tax rate though there are some
gaps in the IHS Herold Inc. series. Where available the ratio of total income tax expense to
earnings before tax is used to fill these gaps.

The Adelman variables, discount rate ($r^*$) and rate of rate of decrease in production ($a$) are
also collected for the firms in the sample. The proxy used for the discount rate is the weighted
average cost of capital, which is obtained from IHS Herold Inc. The estimate for the rate of decline
in extraction is based on Adelman’s limiting result for an oil producer’s total reserves, $R = Q/a$.
(Adelman (1990)). Rearranging this result gives $a = Q/R$. Thus, the ratio of production for the
period to total reserves at the end of the period should provide an approximation for the rate of
decline in extraction. The measure of developed reserves is the ratio of reported developed reserves
to total reserves.  

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15 This consumer price index is not seasonally adjusted. The monthly index values are matched to the date of the IHS
Herold Inc. report, or the 10K reports where data is obtained from this source, when calculating real values.
16 While this ratio should lie between 0% and 100% there are two producers, Petrokazakhstan in 1996 and 1997 and
MOL in 2008, for whom IHS Herold Inc. reported negative undeveloped reserves, resulting in developed reserves that
exceeded total reserves. These numbers had little impact on analysis and so they remain in the final data set.
The initial sample of crude oil producers consists of 538 companies (4989 firm-year observations) spanning the period from 1992 to 2008. There are a number of producers with incomplete data and this reduces the sample available for the basic Hotelling tests to 409 firms (3303 firm-year observations). Further, the existence of extreme values warrants the use of a filter to temper the impact of these values on final analysis. Three filters are applied to both the market value of upstream assets and the price net of extraction costs. The first is a 2% filter which excludes the largest 1% and the smallest 1% of values for these two variables, the second is a 5% filter with exclusion of the largest and smallest 2.5% of values and the third is a 10% filter, with exclusion of the largest and smallest 5% of values. As there is not much variation in analysis of the three filtered data sets, only the results from the 5% filtered data set are reported in the tables that follow. Descriptive statistics for the key variables are reported in Table 2 for the 5% filtered data.

[Insert Table 2 about here]

IV. Results

Hypotheses are tested within a fixed effects panel model, using the Huber/White/sandwich robust standard errors. Two models are fitted to the data. The first is a simple two variable test of the Hotelling relation and this is reported in the second column under the heading “Hotelling” while a test of the Adelman model is reported in column 3 under the heading “Adelman”. In all cases the estimated models are statistically significant at the 5% level of significance.

Hypothesis 1 focuses on the key relation reported in the literature: that in the absence of taxes and given constant costs of extraction, the market value of crude oil reserves varies one-to-one with the price of the crude oil and gas reserves net of extraction costs. Adelman proposes that this relation is not fixed over time and will vary with producer discount rate and production rate. Hypothesis 2 provides a test of the impact of corporate taxes on these relationships, using effective tax rate as a proxy for the marginal producer tax rate. Hypothesis 3 addresses the possibility of

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17 It should be noted that the number of firms do not relate one-for-one with the number of firm-years in this summary as variables were missing for some years for some firms. It is not always the case that a variable is missing in all years for a particular firm.
regulatory impact arising from differences that might exist between producers operating mainly in the USA and Canada and those operating more broadly. If regulatory differences are important then there will be differences between the two groups in the coefficients estimated when fitting equation (2) and equation (10) to the data (Davis and Moore (1998); McDonald (1994)). Finally, hypothesis 4 focuses on the impact of the level of development of the reserves held by the producer.

5.1 Test of Hypothesis 1, $\beta = 1$

The test of Hypothesis 1 is based on the model identified in Equations (2) and (10) and the estimated coefficients are reported in Panels A and B of Table 3. Full sample tests of hypothesis 1 are reported in Panel A. For the Hotelling model to be supported, the estimated coefficient for net price should be close to one, perhaps varying somewhat with changes in the impact of taxes over time. Factors such as risk or production rate should have no explanatory power over this relation (Miller and Upton (1985a)). The net price coefficient of 0.2324, (Hotelling column of Panel A) is positive, though statistically significantly less than one (t statistic = -37.75). More importantly, the Adelman model results (Panel A) show that the relation between reserve value and net price is not fixed, but is a function of production rate, consistent with Adelman’s prediction. The proxy for discount rate is not statistically significant, though it is possible that the firm-specific discount rate is captured by the individual producer fixed term.

[Insert Table 3, Panel A and B, about here]

Where a producer is involved in activities other than upstream activities, the book value of assets not associated with oil and gas extraction activities is deducted from the market value of the producer to estimate the market value of the producer’s reserves. This adjustment could result in measurement error. Thus, it is important to test for differences in the magnitude and statistical significance of estimated coefficients across these two groups of producers (Grain and Jamal (1991)). Equation (2) and equation (10) are re-estimated including a dummy variable set to one
where the producer requires a book value based adjustment for its downstream activities or set to zero where the producer focuses on crude oil and gas extraction. The results of this analysis are reported in Panel B of Table 3 and while the basic results reported in Panel A remain, there is evidence of a statistically significant difference, at the 10% level, in net price coefficient reported in the Hotelling column of Panel B. This suggests that more diversified producers have a statistically significantly lower net price coefficient. The F test for a difference between upstream and downstream producers is statistically significant though analysis of the individual t tests suggests that this effect is mainly evident in the ratio of production to reserves. There is a statistically significant difference in production ratio with upstream producers exhibiting a greater production to reserves ratio on average.

The key result to be drawn from this analysis is that the relation existing between the value of crude oil reserves and the price of the crude oil and gas reserves net of extraction costs is a function of production rate. While the proxy for the producer’s discount rate has no statistically significant explanatory power\(^\text{18}\) it is clear from this analysis that this relation is not fixed and so the Hotelling prediction of \(\beta = 1\) is clearly rejected for the sample of crude oil and gas producers included in this study and, indeed, this restriction is rejected in all of the analysis reported in the following tests.

5.2 Test of Hypothesis 2, Impact of corporate taxes

The test of hypothesis 2 is reported in Table 4 where the results from fitting equation (11) and equation (3). Miller and Upton argue that while taxes may have an impact on the relation that exists between the value of reserves and the market price of the reserves net of extraction costs it would be fairly small as producers take actions to minimise their tax exposure. They suggest, given the generous tax regime in the USA and in Canada, that producers could conceivably reduce tax associated with extraction of crude oil and gas to zero. While this has not been disputed in the literature there is little attempt to analyse the impact of taxes on the valuation of the reserves.

\(^{18}\) This lack of statistical significance is probably due to multicollinearity.
Marginal tax rates are not available for the firms in the sample but an effective tax rate is provided by IHS Herold Inc. and this is used as a proxy for the marginal tax rate.

The coefficient on net price after tax is statistically significantly different from zero with a value of 0.0398. This is also statistically significantly different from one (t statistic = -65.01). The magnitude of this coefficient is considerably lower than the before tax estimate of 0.2324 reported in Table 3. Consistent with Table 3, the coefficient for the ratio of production to reserves is positive and statistically significant. The coefficient for the discount rate proxy is statistically insignificant though it is negative which is predicted in the Adelman model.

In summary, while the coefficient values are somewhat smaller in magnitude, the basic result identified in Table 3 still holds. The relation existing between the value of crude oil reserves and the price of the crude oil and gas reserves net of extraction costs is not constant. Indeed, it would appear to be a function of the ratio of production to reserves. While these results do not support the Hotelling model they do provide some support the model proposed by Adelman.

5.3 Test of Hypothesis 3, Impact of regulation

Given the international nature of the producers included in the sample it is possible to test for a differences in the estimated coefficients for USA and Canadian firms versus firms that tend to operate more internationally. A dummy variable is constructed with a value of one where a producer’s crude oil and gas extraction occurs primarily in the either the USA or Canada and value of zero otherwise. It has been argued that USA and Canadian crude oil and gas production is heavily regulated (McDonald (1994 )) and so it is expected that the coefficient estimated for this dummy variable might shed some light on the impact of this regulation (see Table 5). The basic results hold though none of the dummy variable based coefficient estimates are statistically significant and the F-test for difference across each of the three estimated coefficients in the
Adelman model is not statistically significant. Thus, the regulatory differences that might exist between the USA and Canadian producers and producers operating mainly in other countries of the world do not explain the results observed in the paper.

[Insert Table 5 about here]

5.4 Impact of proven reserve development

As indicated, the production rate has considerable explanatory power over the results reported above though it is also possible that if the market values producers with a higher production rate then the financial markets may also value producers with greater levels of developed reserves as distinct from undeveloped reserves. Crude oil can be extracted with greater certainty from proven developed reserves and this may add value to producers, with higher levels of developed reserves being preferred to low levels of developed reserves (all else held constant). The ratio of developed reserves to total reserves is included in the basic Hotelling and Adelman models and the results of statistical analyses reported in Table 6. While the results reported for the Hotelling model and the Adelman in previous analysis remain essentially unchanged the estimate coefficient for the ratio of developed reserves to total reserves is statistically significant and positive. It would appear that the value of the producer’s reserves is increasing in proportion to developed reserves that make up the producer’s reserves.

V. Conclusion

The valuation of crude oil and gas producers is an important task for both management and investors (present and future) yet valuation of crude oil and gas reserves is complex. While traditional discounted cash flow approaches can be used, the simpler approach to valuation implicit in the Hotelling model is the subject of considerable empirical analysis and debate. There is some initial support for the Hotelling model but more recent literature is less accommodating.

Previous empirical studies have focused on fairly short time periods with an emphasis on cross-sectional or pooled regression analysis. Our study spans an 18-year period from 1992 to 2008
and we find no support for the simple Hotelling prediction of a one-to-one relation between market value per unit of crude oil and gas reserves and the price, net of extraction costs. Indeed, the estimated parameters, while being positive, are economically and statistically significantly less than the predicted value of one. Further, when the simple Hotelling model is expanded to include proxies for discount rate and the production ratio there is evidence that the relation between the value per unit of reserves and the price net of extraction costs is a function of the firm’s production ratio. This finding is inconsistent with the simple Hotelling prediction. These results are not sensitive to whether the producer specialises in extracting USA or Canadian crude oil and gas and so it would seem that the restrictive regulation evident in the USA and Canada does not explain the key results of this analysis. The results are sensitive to whether the producer focuses on extraction alone or is more diversified (either vertically or horizontally) with production ratio having less explanatory power for the diversified firms.

We also look into the question of whether reserve development has an impact on the value of a crude oil and gas producer’s reserves. Analysis of this question is not apparent in the literature to date. We find that the ratio of developed reserves to total reserves is positively related with the market value of these reserves. Contrary to expectations, the market appears to be sensitive to the level of uncertainty associated with the stated reserves held by a producer, valuing developed reserves more highly than undeveloped reserves.

All in all, these results suggest a more complex model of crude oil and gas reserve value than suggested by the basic Hotelling model. Perhaps the main conclusion drawn from this analysis is that the Hotelling model is not a complete model of reserve valuation. Production ratio does have an impact on the value of a crude oil and gas producer. The market attaches greater value to those producers who are able to extract their crude oil and gas more quickly. While it could be argued this result just reflects a bias for present consumption over future consumption, an alternate explanation is that the greater extraction rate may reflect a higher quality reserve that requires less complex extraction technology, lower production risk and is simpler to operate. In effect, this result
could suggest that the market is prepared to pay more for higher quality crude oil and gas reserves that are relatively easy to extract.

The level of development of a producer’s reserves is also reflected in the market value of a crude oil and gas producer. The strong positive relation between the proportion of reserves that are developed and market value is consistent with the argument that the more developed the reserves the less risky the project. With increasing levels of development both the quality and quantity of the reserves are better understood and thus more accurately reflected in the value of the firm.

Ultimately, crude oil and gas reserves are finite in number. Each reserve has its own set of unique characteristics. Perhaps it is to be expected that the value of crude oil and gas reserves should reflect the unique characteristics of that reserve, both in terms of feasible production rate and better understanding of the reserve as reflected in the level of development of the reserves.
Appendix, The Hotelling model

Miller and Upton model the value of an exhaustible natural resource project based on the work of Hotelling (1931). The value of an exhaustible resource project is expressed in terms of its present value where the resource is extracted over a series of periods, \( t = 0,1,\ldots,N \). The resource is extracted at period \( t \) at a cost, \( C_t = C_t(q_t, Q_t) \), with current period extraction, \( q_t \), and cumulative level of extraction at time \( t \), \( Q_t = \sum_{s=0}^{t} q_s \), with \( C_{q_t} = \partial C_t / \partial q_t > 0 \) and \( C_{Q_t} = \partial C_t / \partial Q_t \geq 0 \). This extraction cost function includes the impact of both current production as well as allowing for increases in costs as the reserve nears exhaustion. Given a certain world, tax rate of \( \tau \), fixed discount (or interest) rate after tax, \( r \), and constant resource price, the present value of the resource project, \( V_0 \), is written:

\[
V_0 = \sum_{t=0}^{N} \left( p_t q_t - C_t(q_t, Q_t) \right)(1 - \tau) \left( 1 + r \right)^t
\]

(A1)

As available reserves are limited to \( R_0 \) then total production cannot exceed this limit over the life of the project. This gives rise to the constraint:

\[
\sum_{t=0}^{N} q_t \leq R_0
\]

(A2)

The Lagrangian, with multiplier, \( \lambda \), is written:

\[
L(q, \lambda) = \sum_{t=0}^{N} \left( p_t q_t - C_t(q_t, Q_t) \right)(1 - \tau) \left( 1 + r \right)^t + \lambda \left( R_0 - \sum_{t=0}^{N} q_t \right)
\]

(A3)

The first order conditions can be written:

\[
\frac{\partial L(q, \lambda)}{\partial q_t} = \frac{\left( p_t - C_{q_t} \right)(1 - \tau)}{\left( 1 + r \right)^t} - \sum_{s=t}^{N} \frac{C_{Q_s}(1 - \tau)}{\left( 1 + r \right)^s} = \lambda \text{ for } t = 0,1,\ldots,N
\]

(A4)

In equilibrium, equation (4) allows comparison of the constraint at different points of time.

\[
\frac{p_t - C_{q_t}}{\left( 1 + r \right)^t} - \sum_{s=t}^{N} \frac{C_{Q_s}(1 - \tau)}{\left( 1 + r \right)^s} = p_0 - C_{q_0} - \sum_{s=0}^{N} \frac{C_{Q_s}(1 - \tau)}{\left( 1 + r \right)^s}
\]

(A5)
With some rearrangement it is apparent that the net price at some point \( t \) is a function of the net price now, the rate of interest and increasing extraction costs.

\[
p_t - C_q t = (p_0 - C_{q_0})(1 + r)^t + \left( \sum_{s=1}^{N} \frac{C_{Q_s}(1-\tau)}{(1 + r)^s} - \sum_{s=0}^{N} \frac{C_{Q_s}(1-\tau)}{(1 + r)^s} \right)(1 + r)^t
\]

\[
p_t - C_q t = (p_0 - C_{q_0})(1 + r)^t - \left( \sum_{s=0}^{t-1} \frac{C_{Q_s}(1-\tau)}{(1 + r)^s} \right)(1 + r)^t \text{ for } t = 0, 1, ..., N \quad (A6)
\]

To capture the difference in average and marginal costs arising from non-constant returns to scale, define:

\[
F_t = C_t(q_t, Q_t) - C_{q_t}q_t \text{ or } C_t(q_t, Q_t) = F_t + C_{q_t}q_t \quad (A7)
\]

Substitute equation (7) into equation (1) and rearrange to give:

\[
V_0 = \sum_{t=0}^{N} \frac{q_t \left( p_t - C_{q_t} \right)(1 + r)^t - \frac{F_t}{q_t}}{(1 + r)^t} \quad (1 - \tau)
\]

Given equation (6) then this can be re written as:

\[
V_0 = \sum_{t=0}^{N} \frac{q_t \left( p_0 - C_{q_0} \right)(1 + r)^t - \frac{F_t}{q_t}}{(1 + r)^t} \quad (1 - \tau) = \left( p_0 - C_{q_0} \right)(1 - \tau) \sum_{t=0}^{N} q_t - \sum_{t=0}^{N} F_t(1 - \tau) - \sum_{t=1}^{N} q_t \sum_{s=0}^{t-1} \frac{C_{Q_s}(1 - \tau)}{(1 + r)^s}
\]

\[
= \left( p_0 - C_{q_0} \right)(1 - \tau)R_0 - \sum_{t=0}^{N} F_t(1 - \tau) - \sum_{t=1}^{N} q_t \sum_{s=0}^{t-1} \frac{C_{Q_s}(1 - \tau)}{(1 + r)^s}
\]

\[
= \left( p_0 - C_{q_0} \right)(1 - \tau)R_0 - \sum_{t=0}^{N} F_t(1 - \tau) - \sum_{t=1}^{N} q_t \sum_{s=0}^{t-1} \frac{C_{Q_s}(1 - \tau)}{(1 + r)^s}
\quad (A8)
\]

Divide through by \( R_0 \) and assume that the two right hand terms are constant (Miller and Upton (1985a)) then the value of the reserve per unit of resource is defined as:

\[
\frac{V_0}{R_0} = \left( p_0 - C_{q_0} \right)(1 - \tau) - K_1 - K_2 \quad (A9)
\]
Following Miller and Upton, it is assumed the tax rate is zero, the average extraction cost equals marginal extraction costs consistent with constant returns to scale \( c_t = C q_t \) and the second term in equation (7) is set to zero, the value of an exhaustible natural resource is a function of current price net of extraction costs and the marginal tax rate (Miller and Upton (1985a)).

\[
\frac{V_0}{R_0} = (p_0 - c_0)(1 - \tau)
\]  

(A10)
References


Table 1, Sample construction

<table>
<thead>
<tr>
<th></th>
<th>Firms</th>
<th>Firm-years</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial sample</td>
<td>533</td>
<td>4989</td>
</tr>
<tr>
<td>Missing lifting cost, number of shares or share price or reserve information</td>
<td>124</td>
<td>1686</td>
</tr>
<tr>
<td>Number of observations available for analysis</td>
<td>409</td>
<td>3303</td>
</tr>
<tr>
<td>- Available for analysis with 2% filter</td>
<td>403</td>
<td>3176</td>
</tr>
<tr>
<td>- Available for analysis with 5% filter</td>
<td>396</td>
<td>2996</td>
</tr>
<tr>
<td>(used in analysis reported in following tables)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Available for analysis with 10% filter</td>
<td>338</td>
<td>2710</td>
</tr>
</tbody>
</table>
Both nominal and real values (December 2008 dollars) are reported in this table, though real values are used in the analysis that follows. The value of crude oil and natural gas reserves per unit of reserves and the weighted average of the crude oil price and natural gas price, net of extraction costs (Net price) are calculated for each firm, for each year that firm data is reported in the IHS Herold Inc. data set. The producer’s weighted average cost of capital (WACC) is used as a proxy for the its required rate of return. The ratio of production to total reserves (Prod/reserves) is used to capture the constant decrease in production over the life of the reserve and the proxy for developed proven reserves is the ratio of developed proven reserves to total proven reserves (Dev/Reserves).

Summary statistics reported in this table relate to the 5% filter based data set.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Observations available</th>
<th>Mean</th>
<th>Standard Deviation</th>
<th>Minimum</th>
<th>Maximum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Market value of reserves</td>
<td>2996</td>
<td>12.90</td>
<td>12.37</td>
<td>0.51</td>
<td>103.83</td>
</tr>
<tr>
<td>Real market value of reserves</td>
<td>2996</td>
<td>14.95</td>
<td>13.52</td>
<td>0.76</td>
<td>110.84</td>
</tr>
<tr>
<td>Net price</td>
<td>2996</td>
<td>24.07</td>
<td>15.15</td>
<td>5.50</td>
<td>66.58</td>
</tr>
<tr>
<td>Real net price</td>
<td>2996</td>
<td>27.59</td>
<td>15.20</td>
<td>7.79</td>
<td>66.65</td>
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<tr>
<td>WACC</td>
<td>2339</td>
<td>10.29</td>
<td>9.08</td>
<td>-5.63</td>
<td>350.15</td>
</tr>
<tr>
<td>Prod/Reserves</td>
<td>2995</td>
<td>27.75</td>
<td>18.60</td>
<td>0.13</td>
<td>558.19</td>
</tr>
<tr>
<td>Dev/Reserves</td>
<td>2927</td>
<td>70.07</td>
<td>18.92</td>
<td>0.73</td>
<td>217.29</td>
</tr>
</tbody>
</table>
Table 3, Test of Miller and Upton model, no taxes

The Hotelling (1931) prediction of a one-to-one relation between real market value of crude oil and natural gas reserves per unit of reserves (Market value) and real weighted average of the crude oil price and natural gas price net of extraction costs (Net price) is tested using fixed effects panel analysis. Both variables are expressed in terms of 2008 dollars. This model is extended to test the Adelman (1990) argument that the Hotelling relation is not constant, rather it is a function of the producer’s discount rate and production rate. The discount rate and the production rate variables enter the model used in this study as interaction terms where the interaction is with net price. The discount rate proxy is an estimate of the producer’s weighted average cost of capital (WACC) supplied by IHS Herold Inc. The ratio of production to total reserves (Prod/reserves) is used to capture the constant decrease in production over the life of the reserve. Panel A provides analysis of the Hotelling model using all available firms, analysis of the Adelman model and separate analysis of the Hotelling model using a data set that is matched to the Adelman model data set (Hotelling (matched)). Panel B tests for significant difference between those firms involved only in oil and gas extraction, or upstream activities, and those firms that are more diverse in nature including oil and gas extraction as well as refining and other activities or downstream activities. N is the number of producer-year observations in the sample. Producers refer to the number of individual producers falling with in the sample at some stage in the 18-year period of the study. An F-statistic for statistical significance of the model is reported as well as the Pearson correlation coefficient for correlation between the individual producer fixed effect terms and the explanatory variables (u, Xb). An R-square value is also reported for the model. Tests of the Hotelling model restrictions include an F-test for joint significance of the discount rate and the production rate coefficients as well as a t-test for the net price coefficient being equal to one and these are reported in Panel A. Panel B includes an F-test for the joint significance of the discount rate and the production rate as well as for the difference between those producers with downstream activities and those without. Robust standard errors are calculated using the Huber/White/sandwich estimator. * (+) is statistically significant at the 5% (10%) level of significance.

Panel A, All firms

<table>
<thead>
<tr>
<th>Variable</th>
<th>Hotelling</th>
<th>Hotelling (matched)</th>
<th>Adelman</th>
</tr>
</thead>
<tbody>
<tr>
<td>Net price</td>
<td>0.2324*</td>
<td>0.2336*</td>
<td>0.1010*</td>
</tr>
<tr>
<td></td>
<td>(11.43)</td>
<td>(13.14)</td>
<td>(2.33)</td>
</tr>
<tr>
<td>WACC x Net price</td>
<td>-</td>
<td>-</td>
<td>0.0010</td>
</tr>
<tr>
<td></td>
<td>-</td>
<td>-</td>
<td>(0.81)</td>
</tr>
<tr>
<td>Prod/reserves x Net price</td>
<td>-</td>
<td>-</td>
<td>0.0043*</td>
</tr>
<tr>
<td></td>
<td>-</td>
<td>-</td>
<td>(3.06)</td>
</tr>
<tr>
<td>N</td>
<td>2996</td>
<td>2339</td>
<td>2339</td>
</tr>
<tr>
<td>Producers</td>
<td>396</td>
<td>338</td>
<td>338</td>
</tr>
<tr>
<td>F-test for significance of regression</td>
<td>130.62*</td>
<td>172.63*</td>
<td>64.62*</td>
</tr>
<tr>
<td>Correlation (u, Xb)</td>
<td>0.10</td>
<td>0.09</td>
<td>0.19</td>
</tr>
<tr>
<td>R-Square</td>
<td>0.11</td>
<td>0.11</td>
<td>0.22</td>
</tr>
<tr>
<td>Discount rate and production rate coefficients jointly equal to zero (F-test)</td>
<td>-</td>
<td>-</td>
<td>4.84*</td>
</tr>
<tr>
<td>Net price coefficient equal to one (t-test)</td>
<td>-37.75*</td>
<td>-43.10*</td>
<td>-20.78*</td>
</tr>
</tbody>
</table>
Panel B, Analysis of upstream versus downstream crude oil and gas producers

<table>
<thead>
<tr>
<th>Variable</th>
<th>Hotelling (downstream included &amp; matched)</th>
<th>Hotelling (no downstream included &amp; matched)</th>
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<tr>
<td>Net price</td>
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<tr>
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<tr>
<td>WACC x Net price</td>
<td>-</td>
<td>-</td>
<td>0.0016</td>
<td>0.0010</td>
</tr>
<tr>
<td></td>
<td>-</td>
<td>-</td>
<td>(0.66)</td>
<td>(0.72)</td>
</tr>
<tr>
<td>Prod/reserves x Net price</td>
<td>-</td>
<td>-</td>
<td>0.0009</td>
<td>0.0051*</td>
</tr>
<tr>
<td></td>
<td>-</td>
<td>-</td>
<td>(1.56)</td>
<td>(3.93)</td>
</tr>
<tr>
<td>N</td>
<td>629</td>
<td>1495</td>
<td>629</td>
<td>1495</td>
</tr>
<tr>
<td>Producers</td>
<td>97</td>
<td>242</td>
<td>97</td>
<td>242</td>
</tr>
<tr>
<td>F-statistic for significance of regression</td>
<td>71.15*</td>
<td>128.94*</td>
<td>27.81*</td>
<td>48.31*</td>
</tr>
<tr>
<td>Corr (u,Xb)</td>
<td>-0.07</td>
<td>0.12</td>
<td>-0.07</td>
<td>0.27</td>
</tr>
<tr>
<td>R-square</td>
<td>0.07</td>
<td>0.13</td>
<td>0.08</td>
<td>0.28</td>
</tr>
<tr>
<td>Discount rate and production rate coefficients jointly equal to zero (F-test)</td>
<td>-</td>
<td>-</td>
<td>1.52</td>
<td>7.73*</td>
</tr>
<tr>
<td>Net price coefficient equal to one (t-test)</td>
<td>-35.96*</td>
<td>-31.64*</td>
<td>-21.58*</td>
<td>-21.38*</td>
</tr>
<tr>
<td>F-test or t-test for difference between upstream and downstream producers coefficients</td>
<td>-</td>
<td>-2.39*</td>
<td>-</td>
<td>3.59*</td>
</tr>
</tbody>
</table>
Table 4, Test of Miller and Upton model, adjusted using effective tax rate

The Hotelling (1931) prediction of a one-to-one relation between real market value of crude oil and natural gas reserves per unit of reserves (Market value) and real weighted average of the crude oil price and natural gas price net of extraction costs (Net price), adjusted for tax using the effective tax rate, is tested using fixed effects panel analysis. Both variables are expressed in terms of 2008 dollars. This model is extended to test the Adelman (1990) argument that the Hotelling relation is not constant, rather it is a function of the producer’s discount rate and production rate. The discount rate and the production rate variables enter the model used in this study as interaction terms where the interaction is with net price. The discount rate proxy is an estimate of the producer’s weighted average cost of capital (WACC) supplied by IHS Herold Inc. The ratio of production to total reserves (Prod/reserves) is used to capture the constant decrease in production over the life of the reserve. Panel A provides analysis of the Hotelling model using all available firms, analysis of the Adelman model and separate analysis of the Hotelling model using a data set that is matched to the Adelman model data set (Hotelling (matched)). N is the number of producer-year observations in the sample. Producers refers to the number of individual producers falling with in the sample at some stage in the 18-year period of the study. An F-statistic for statistical significance of the model is reported as well as the Pearson correlation coefficient for correlation between the individual producer fixed effect terms and the explanatory variables (u, Xb). The R-square value for the regression is also reported. Tests of the Hotelling model restrictions include an F test for the joint significance of the discount rate and the production rate as well as t-tests for the net price coefficient being equal to one. Robust standard errors are calculated using the Huber/White/sandwich estimator. * (+) is statistically significant at the 5% (10%) level of significance.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Hotelling</th>
<th>Hotelling (matched)</th>
<th>Adelman</th>
</tr>
</thead>
<tbody>
<tr>
<td>Net price (1 - effective tax rate)</td>
<td>0.0398*</td>
<td>0.0821*</td>
<td>0.0301</td>
</tr>
<tr>
<td></td>
<td>(2.70)</td>
<td>4.94</td>
<td>(1.10)</td>
</tr>
<tr>
<td>WACC x Net price x (1 - effective tax rate)</td>
<td>-</td>
<td>-</td>
<td>-0.0001</td>
</tr>
<tr>
<td></td>
<td>-</td>
<td>-</td>
<td>(-0.04)</td>
</tr>
<tr>
<td>Prod/reserves x Net price x (1 - effective tax rate)</td>
<td>-</td>
<td>-</td>
<td>0.0016*</td>
</tr>
<tr>
<td></td>
<td>-</td>
<td>-</td>
<td>(2.57)</td>
</tr>
<tr>
<td>N</td>
<td>2996</td>
<td>2339</td>
<td>2339</td>
</tr>
<tr>
<td>Producers</td>
<td>396</td>
<td>338</td>
<td>338</td>
</tr>
<tr>
<td>F-statistic for significance of regression</td>
<td>7.26*</td>
<td>24.42*</td>
<td>11.04*</td>
</tr>
<tr>
<td>Corr (u,Xb)</td>
<td>0.07</td>
<td>0.07</td>
<td>0.15</td>
</tr>
<tr>
<td>R-square</td>
<td>0.02</td>
<td>0.04</td>
<td>0.09</td>
</tr>
<tr>
<td>F-test for discount rate and production rate proxy coefficients = 0</td>
<td>-</td>
<td>-</td>
<td>3.36*</td>
</tr>
<tr>
<td>Net price t-test for $\beta = 1$</td>
<td>-65.01*</td>
<td>-55.27*</td>
<td>-35.36*</td>
</tr>
</tbody>
</table>
Table 5, Test of Miller and Upton model, A test of the impact of USA and Canadian regulation

The Hotelling (1931) prediction of a one-to-one relation between real market value of crude oil and natural gas reserves per unit of reserves (Market value) and real weighted average of the crude oil price and natural gas price net of extraction costs (Net price) is tested using fixed effects panel analysis. Both variables are expressed in terms of 2008 dollars. This model is extended to test the Adelman (1990) argument that the Hotelling relation is not constant, rather it is a function of the producer’s discount rate and production rate. The discount rate and the production rate variables enter the model used in this study as interaction terms where the interaction is with net price. The discount rate proxy is an estimate of the producer’s weighted average cost of capital (WACC) supplied by IHS Herold Inc. The ratio of production to total reserves (Prod/reserves) is used to capture the constant decrease in production over the life of the reserve. The reported results include analysis of the Hotelling model using all available firms, analysis of the Adelman model and separate analysis of the Hotelling model using a data set that is matched to the Adelman model data set (Hotelling (matched)). N is the number of producer-year observations in the sample. Producers refers to the number of individual producers falling with in the sample at some stage in the 18-year period of the study. F-statistics are reported for the statistical significance of the model, for statistically significant differences between the model estimated for US and Canadian producers relative to other producers and to assess the statistical importance of the discount rate and the production rate within the Adelman (1990) model. The R-square value for the regression is also reported. Robust standard errors are calculated using the Huber/White/sandwich estimator. * (+) is statistically significant at the 5% (10%) level of significance.
<table>
<thead>
<tr>
<th>Variable</th>
<th>Hotelling (USA &amp; Canada)</th>
<th>Hotelling (Other)</th>
<th>Adelman USA &amp; Canada</th>
<th>Adelman (Other)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Net price</td>
<td>0.2369*</td>
<td>0.2253*</td>
<td>0.1267*</td>
<td>-0.0247</td>
</tr>
<tr>
<td></td>
<td>11.05</td>
<td>7.13</td>
<td>2.81</td>
<td>-0.26</td>
</tr>
<tr>
<td>WACC x Net price</td>
<td>-</td>
<td>-</td>
<td>0.0006</td>
<td>0.0047</td>
</tr>
<tr>
<td></td>
<td>-</td>
<td>-</td>
<td>0.37</td>
<td>0.96</td>
</tr>
<tr>
<td>Prod/reserves x Net price</td>
<td>-</td>
<td>-</td>
<td>0.0036*</td>
<td>0.0073*</td>
</tr>
<tr>
<td></td>
<td>-</td>
<td>-</td>
<td>2.66</td>
<td>2.38</td>
</tr>
<tr>
<td>N</td>
<td>1664</td>
<td>675</td>
<td>1664</td>
<td>675</td>
</tr>
<tr>
<td>Producers</td>
<td>241</td>
<td>97</td>
<td>241</td>
<td>97</td>
</tr>
<tr>
<td>F-statistic for significance of regression</td>
<td>122.01*</td>
<td>50.83*</td>
<td>44.99*</td>
<td>19.56*</td>
</tr>
<tr>
<td>Corr (u,Xb)</td>
<td>0.12</td>
<td>0.04</td>
<td>0.20</td>
<td>0.19</td>
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<tr>
<td>R-square</td>
<td>0.13</td>
<td>0.08</td>
<td>0.21</td>
<td>0.27</td>
</tr>
<tr>
<td>Discount rate and production rate coefficients jointly equal to zero (F-test)</td>
<td>-</td>
<td>-</td>
<td>3.56*</td>
<td>3.27*</td>
</tr>
<tr>
<td>Net price coefficient equal to one (t-test)</td>
<td>-35.58*</td>
<td>-24.52*</td>
<td>-19.37*</td>
<td>-10.89*</td>
</tr>
<tr>
<td>F-test or t-test for difference in coefficients between USA and Canadian focused producers and other producers</td>
<td>-</td>
<td>0.31</td>
<td>-</td>
<td>0.72</td>
</tr>
</tbody>
</table>
Table 6, The impact of the proven developed reserves relative to total reserves

The Hotelling (1931) prediction of a one-to-one relation between real market value of crude oil and natural gas reserves per unit of reserves (Market value) and real weighted average of the crude oil price and natural gas price net of extraction costs (Net price) is tested using fixed effects panel analysis. Both variables are expressed in terms of 2008 dollars. This model is extended to test the Adelman (1990) argument that the Hotelling relation is not constant, rather it is a function of the producer’s discount rate and production rate. The discount rate and the production rate variables enter the model used in this study as interaction terms where the interaction is with net price. The discount rate proxy is an estimate of the producer’s weighted average cost of capital (WACC) supplied by IHS Herold Inc. The ratio of production to total reserves (Prod/reserves) is used to capture the constant decrease in production over the life of the reserve. The ratio of developed proven reserves to total proven reserves, Dev/Reserves, are also included in the model to capture the impact on producer value of the ratio of proven developed reserves to total reserves. Results reported in the this table include analysis of the Hotelling model using all available firms, analysis of the Adelman model and separate analysis of the Hotelling model using a data set that is matched to the Adelman model data set (Hotelling (matched)). N is the number of producer-year observations in the sample. Producers refers to the number of individual producers falling with in the sample at some stage in the 18-year period of the study. An F-statistic for statistical significance of the model is reported as well as the Pearson correlation coefficient for correlation between the individual producer fixed effect terms and the explanatory variables (u, Xb). An R-square value is also reported for the model. Tests of the Hotelling model restrictions include an F-test for joint significance of the discount rate and the production rate coefficients as well as a t-test for the net price coefficient being equal to one and these are reported in Panel A. Panel B includes an F-test for the joint significance of the discount rate and the production rate as well as for the difference between those producers with downstream activities and those without. Robust standard errors are calculated using the Huber/White/sandwich estimator. * (+) is statistically significant at the 5% (10%) level of significance.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Hotelling</th>
<th>Hotelling (matched)</th>
<th>Adelman</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Net price</td>
<td>0.2331*</td>
<td>0.2345*</td>
<td>0.1116*</td>
</tr>
<tr>
<td></td>
<td>(11.14)</td>
<td>(12.92)</td>
<td>(2.60)</td>
</tr>
<tr>
<td>WACC x Net price</td>
<td></td>
<td></td>
<td>0.0010</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(0.82)</td>
</tr>
<tr>
<td>Prod/reserves x Net price</td>
<td></td>
<td></td>
<td>0.0038*</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(2.86)</td>
</tr>
<tr>
<td>Dev/reserves</td>
<td>0.1210*</td>
<td>0.1025*</td>
<td>0.0597*</td>
</tr>
<tr>
<td></td>
<td>(4.44)</td>
<td>(3.63)</td>
<td>(2.18)</td>
</tr>
<tr>
<td>N</td>
<td>2927</td>
<td>2295</td>
<td>2295</td>
</tr>
<tr>
<td>Producers</td>
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<td>333</td>
<td>333</td>
</tr>
<tr>
<td>F-test for significance of</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>regression</td>
<td>62.20*</td>
<td>83.59*</td>
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<td>Correlation (u, Xb)</td>
<td>0.02</td>
<td>0.06</td>
<td>0.16</td>
</tr>
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<td>R-Square</td>
<td>0.10</td>
<td>0.11</td>
<td>0.20</td>
</tr>
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<td>Discount rate and production rate coefficients jointly equal to zero (F-test)</td>
<td></td>
<td></td>
<td>6.03*</td>
</tr>
<tr>
<td>Net price coefficient equal to one (t-test)</td>
<td>-36.67*</td>
<td>-42.16*</td>
<td>-20.69*</td>
</tr>
</tbody>
</table>
Figure 1, Gas and oil reserves (Millions of Barrels)