Abstract

HARMELING, ERIC JAMES. Upstream Oil in Developing, Non-OPEC Countries: Do Prices Determine Reserve Additions? (Under the direction of Mitchell Renkow.)

This paper presents an empirical study on oil reserve additions in a selection of price-taking, oil-producing countries. The estimation results on a model for reserve additions suggest that nationalization and historical reserve levels are primary factors in exploration and extraction decisions, and provide little evidence that prices provide a short-term incentive to add reserves. The implications for energy security and climate policy are particularly relevant for future policy controls on the market for fossil fuels.

Upstream Oil in Developing, Non-OPEC Countries: Do Prices Determine Reserve Additions?

by
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Biography

Eric Harmeling was born in Camarillo, California, and passed his high school and college years in North Carolina.

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Chapter 1

Introduction

As world populations and economies grow, affordable and accessible energy becomes increasingly important. Energy demand is expected to rise over 70% in developing countries (non-OECD) and around 18% in developed countries (OECD) between 2012 and 2040 (EIA, 2016). Although renewable, clean energy sources have declined in cost and risen in market penetration, nonrenewable fossil fuels have dominated the energy market since the Industrial Revolution. In 2012, fossil fuels comprised nearly 80% of total world energy consumption, making them the main power source for the global economy.

Although fossil fuels will likely take a lesser role in the future of global energy because of their long-lasting effects on the environment (and to a lesser extent, due to their exhaustibility), with the current global energy infrastructure and the projected economic growth rates worldwide, fossil fuels will continue to be in high demand, and in high production, for the remainder of the 21st century.[1] The global consumption of liquid fossil fuels, for instance, is expected to rise from 90 million barrels per day to 121 million, an increase of over 30% between 2012 and 2040 (EIA, 2016). With the rise in consumption of globally traded liquid fuels like petroleum, global prices are also expected to rise in the medium and long-term.

[1] This is particularly the case in the energy market for transportation. The overwhelming majority of vehicles run on petroleum, and no near-term substitute fuel exists.

Reserve additions are crucial to sustaining the supply base of a nonrenewable resource. As the global consumption and extraction of a resource increases, reserves must expand to avoid exhausting the supply base. Assuming convexity in the cost function for successful exploration,[2], and assuming oil producers are profit-maximizing, future hydrocarbon exploration efforts will likely be concentrated in countries with less reserves, since nations with more cumulative reserves, such as OPEC countries, Russia, Canada, and the United States, face steeper marginal costs. If the decision to drill for reserves is based on changes in oil prices and extraction costs, developing countries that produce oil will likely add reserves into the future to sustain their oil production for domestic use and exports.

Although estimates of total undiscovered conventional oil resources vary widely, some studies suggest that a large portion of the world's undiscovered oil resources are located in developing countries. Schenk et al. (2012) estimate that up to 75% of total undiscovered oil resources are located in South America, Africa, North America and the Middle East. Of the regions assessed, the largest average estimates of undiscovered resources are concentrated in South America and Sub-Saharan Africa. If much of the world's undiscovered oil is located in developing countries, learning more about the drivers of exploration and discovery should help to elucidate the future of the global supply of oil. Shifts in prices, might influence the long-run supply (and in turn the long-run price) of oil through current price-takers' decisions to increase, decrease, or maintain their current reserve levels. Similarly, changes in the costs associated with exploration, and the subsequent effects of reserve additions on extraction costs, might drive the decision to explore. Other drivers of reserve changes include technological improvements to oil field estimation methods, international energy or environmental agreements, regime changes, and other unobservable characteristics of incumbent governments and national oil companies.

In this thesis, I examine the determinants of changes in oil reserves. A cursory view of

[2] A standard assumption in the literature is that the difficulty of finding more oil in a region increases with each new discovery. That is, scarcity increases the marginal costs of adding reserves. Pindyck (1978) first introduced a variable marginal cost function in a dynamic nonrenewable resource exploration and extraction problem. I review his paper in section 3.

global oil trends and the theoretical and empirical literature suggests that hydrocarbon exploration depends on the profitability of additional reserves, as measured by oil prices and the combined costs of exploration and extraction. To identify the effects of oil price on reserves, I make the assumption that significant price shifts in the market for fossil fuels are exogenous to reserve changes in my sample and in developing country oil-producers. That is, prices cause changes in reserves, but changes in reserves do not cause price changes. I base this assumption on empirical studies I review in upcoming sections. These indicate that developing nations that do not belong to OPEC are price-takers whose decision to develop oil fields has a negligible impact on world oil prices. The strict exogeneity of prices is an assumption I make for this study, but is liable to change as technology improves and demand for oil increases in non-OECD, non-OPEC countries.

This thesis is organized as follows: I first provide a brief overview of proved reserves and the upstream sector of the petroleum supply chain in Chapter 2. In Chapter 3.1, I discuss the relationship between the scarcity of nonrenewable fossil fuels and the price of fossil fuels. Historically, the Hotelling rule has been used to describe the price paths of nonrenewable natural resources as a negative function of historical and present-day extraction (a positive function of time due to scarcity). Empirical studies have not supported the claim that major shifts in fossil fuel prices, oil in particular, have been primarily driven by scarcity on the supply side, but rather reflective of macroeconomic demand shocks and cartel behavior (Krautkraemer, 1998); (Kilian, 2009); (Livernois, 2009); (Kilian and Hicks, 2013); (Kaiser, 2013); (Juvenal and Petrella, 2015); (Baumeister and Kilian, 2016). The effects of scarcity on prices are likely to be long-run in the presence of other determinants of oil prices. Chapter 3.2 covers some of the determinants of oil prices, including the effects of macroeconomic shocks and financial markets on the price of fossil fuels, and the role of OPEC in setting global oil prices. Empirical evidence has shown that macroeconomic aggregates and financial speculation have caused major shifts in oil prices, with less noticeable price shifts from shocks to the (estimated) supply base. In Chapter 4, I briefly discuss the literature on reserve estimation and valuation. In Chapter 5, I discuss the exploration decision from the perspective of a profit-maximizing firm, following the Farzin (2001) reduced-form model for reserve additions. In Chapter 6, I summarize the data and describe the econometric model, based on the exploration decision framework from Chapter 5, with some additional controls. In Chapter 7, I discuss the results and the relationships between the independent and dependent variables in the estimated model. Chapter 8 reviews the estimation results of several alternative model specifications. In Chapter 9, I discuss the importance of reserves and prices in the context of free-riding and carbon leakage from incomplete international climate policy, following Berg et al. (2002). I then conclude the thesis with a brief review of the empirical results and their policy implications.

Chapter 2

Reserves in the Petroleum Industry

Fossil fuels are nonrenewable and exhaustible, meaning that the global supply of fossil fuels decreases with each unit of fuel that is consumed. Oil is the least abundant of the fossil fuels, and unlike coal and natural gas, is traded on an international market with global prices. The supply chain of the petroleum industry, like other natural resource industries, is comprised of two loosely-defined sectors: an upstream sector, which includes exploration and drilling, and a downstream sector, which is comprised of refining and distribution. Exploration makes up the first step in the petroleum industry's supply chain. Successful exploration efforts and extensions to already-discovered fields have prevented the depletion of fossil fuels by continuously increasing the known amount of fuel that can be produced for consumption. As suppliers in the market for fossil fuels, international oil companies (IOCs) and national oil companies (NOCs) are the entities that control the exploration, extraction, and production process. IOCs and NOCs conduct expensive and risky exploration efforts to ensure that future extraction and production continues.[1]

Prior to investing in full-scale oil exploration efforts, oil companies conduct geological assessments of in-ground resources. Geologists use geostatistical and seismic imaging methods

[1] For publicly traded IOCs, fossil fuel reserves are depletable assets. Expanding reserves is one way to increase market capitalization. Kaiser (2013) and Ewing and Thompson (2016) discuss the role of reserve expansion and reserve trading in the market capitalization of IOCs.

to estimate the location and amount of potential oil reserves in different regions across the world. Drilling occurs in areas estimated to contain profitable amounts of oil, and where oil is discovered, total discoveries are classified as *reserves* based on the estimated probability with which they will be extracted and sold under current economic conditions. Figure 1 illustrates the reserve development process from exploration to production. Prospective resources are estimated and explored in the initial stages of exploration. Contingent resources are then appraised according to their maturity, and lastly classified as reserves as they are prepared for production. These classifications are *proved* reserves (90% probability of ultimate extraction), *probable* reserves (50%), and *possible* reserves (10% - 50%). The present-period cost of producing, which is determined by the technology available and the difficulty of extraction, and the expected return on the estimated oil in a particular location (usually the current price of oil or value of the reservoir to a company's market valuation) determine the "economic conditions" by which reserves are classified.

Reserves are the result of exploratory efforts and are classified based on the certainty that they will be produced. Of all measurements of accumulated resources, proved reserves are associated with the highest certainty of production, being either planned for production, or in reservoirs being prepared for production. The chart in Figure 3 offers a visual aid of the classification of petroleum resources. Of the total petroleum in-place, reserves are the resources that have been discovered and are commercially viable. The Petroleum Resources Management System (PRMS)[2] specifies *commerciality* as a defining characteristic of reserves. According to PRMS, proved reserves, as commercially viable resources, are generally extracted or fully prepared for extraction within five years of their classification (SPE and AAPG, 2007).

Proved reserves have steadily grown with production and consumption since global reserve records have been kept (see Figure 5). Estimates of proved reserves of crude oil rose from around 643 billion barrels worldwide in 1980 to over 1650 billion barrels in 2015, an

[2]To ensure a certain level of consistency throughout global measurements of proved reserves, the Society of Petroleum Engineers, the World Petroleum Council, the American Association of Petroleum Geologists, and the Society of Petroleum Evaluation Engineers, collaboratively designed the Petroleum Resources Management System to define what reserves are and are not.

increase of over 150%.[3] As of 2012, only eight countries (Canada, Iran, Iraq, Kuwait, Russia, Saudi Arabia, United Arab Emirates, and Venezuela) account for more than 80% of the world's reserves (EIA, 2016).

Once the decision to search for new fuel or to extend current reserve fields is made, the success of reserve expansion efforts depends on the drilling and extraction technology available, and on the geological limitations of the area being explored. The yield of successful expansion efforts are then generally revised over time, with the initial estimates underestimated at first (EIA, 2016). Changes in global crude oil proved reserves over the past decade have largely been revisions of discoveries made in OPEC countries and North America in the 2000's, and reflect the volatility of oil prices and events in the macroeconomy (See Figures 6 and 7). Trends in reserve additions show a slowing down in global exploratory efforts in recent years, as prices have remained fairly constant from 2014 to 2016. The *Oil & Gas Journal*'s 2015 proved reserve estimates increased from 2014 levels by just 2 billion barrels (Xu et al., 2015). BP's Statistical Review of World Energy revised estimates of world reserves down from 1700 billion in 2015 to 1697 billion in 2016 (BP, 2016). This is likely because the recent decline in prices has made previously-economical reserves worth less per barrel, or decreases in global prices in previous years made exploratory efforts less profitable.

[3]In 2015, The EIA's World Energy Outlook estimated 1655 billion barrels worldwide and BP's Statiscal Review 1697 billion. 1980 reserves were estimated to be 643 billion barrels by the EIA and 683 billion by BP.

Chapter 3

Pricing Fossil Fuels: Reserves and Oil Prices

3.1 Scarcity and the Dynamic Price and Extraction Paths of Nonrenewable Resources

Nonrenewability plays an important role in the valuation and production of natural resources across time periods. For decades, resource economists have modeled extraction as a dynamic decision constrained by scarcity. Hotelling's rule (Hotelling, 1931) dictates that the emergent price of a nonrenewable natural resource increase at the market interest rate when the marginal costs of extracting the resource remain positive and constant. Under Hotelling's rule, the discounted value of all nonrenewable resource deposits is maximized under a particular extraction path that equalizes the value of profits from extraction over time to foregone investments in the market. The difference between the marginal cost of extracting the resource and the price at which the resource is sold on the market, also called the resource rent, follows the market interest rate.

The assumptions implicit in Hotelling's rule, namely that marginal costs remain constant over time, are not consistent with the market for most nonrenewable resources. In fact, empirical evidence has shown that, contrary to Hotelling's rule, real prices of nonrenewable prices remained the same, and in some cases decreased, over the 20^{th} century, while production, consumption, and reserves increased substantially (Krautkraemer, 1998). The literature has produced some important extensions of Hotelling's rule that depict a more realistic relationship between pricing and extraction and scarcity. These qualifications to the Hotelling story account for changes in extraction costs due to technological change, as well as changes in market conditions, such as the presence of price-setting cartels like OPEC and international oil companies with market power. Some of the nonrenewable natural resource literature has also notably extended Hotelling's rule to include the expansion of the reserve base through exploration and discovery.

Pindyck (1978) was among the first to examine the effects of exploration and discovery on future price and extraction paths. Extending the classic Hotelling framework, Pindyck describes the price path derived from the producer's dynamic extraction and exploration problem as a simple function of the marginal costs of extraction. The marginal costs determine when the producer will extract, and the market price will, with scarcity rents, be above the increasing marginal costs of extraction. Unlike Hotelling, Pindyck assumes the marginal cost of extraction is a positive function of cumulative reserves, where the marginal cost of extraction increases with extraction. He also assumes that resources, while physically exhaustible, are not economically exhaustible under exploration. As a nonrenewable resource is extracted, the remaining extractable supply diminishes, and the marginal cost of extracting the remaining, less-accessible reserves increases. Pindyck extends the Hotelling price path of a nonrenewable resource to be reflective of the increasing marginal extraction cost curve. As the price of a nonrenewable resource increases, the incentives to explore increase, especially when demand is relatively inelastic to price.

In the aggregate, reserve additions from newly discovered deposits offset the effects of scarcity, and suppress increases in marginal extraction cost. Increases in reserve additions, under Pindyck's model, push price increases due to scarcity further into the future by increasing the supply base and decreasing the costs of extraction. The projected price path is then U-shaped under the assumption that initial reserves are zero or very low. Prices are initially high due to scarcity (scarcity in the market, and not scarcity in the ground). Exploration, discovery and subsequent extraction flood the market with the resource and depress prices until it becomes unprofitable to add reserves due to the increasing costs of successful exploration. Prices then increase to reflect the increased marginal costs of extraction as soon as adding reserves becomes unprofitable due to geological constraints.

Other notable extensions to the Hotelling rule introduce non-competitive producers to the market for nonrenewable resources. Salant and Henderson (1978) incorporate anticipated auctions into the dynamic extraction decision of the "competitive fringe" in the monopolistic market for gold. For a competitive producer to keep resources in the ground, the expected price in the future must equal the discounted present-period price. If speculators anticipate decreases in the price due to some unpredictable change in the supply of gold (a government auction in Salant and Henderson's case) at some time in the future, the expected market price for gold prior to the auction must increase at a rate higher than the market interest rate to compensate suppliers for both foregone investments at the market interest rate, and the risk of a price drop following some impending government auction. If the price increases at a sufficiently low rate, competitive suppliers are unwilling to hold gold as an asset (in the ground or as reserves) and extract and sell their nonrenewable stocks, lowering the price. This implies that competitive producers are also unwilling to explore because the extractable reserves added from discovery are not worth the costs of exploration.

The anticipation of a surge in the supply of a globally traded nonrenewable resource alters the price expectations and dynamic extraction decisions of competitive producers, causing production behavior that could affect market prices. Applying the Salant and Henderson anticipations model to the oil market, if competitive oil producers anticipate some unexpected, coordinated sell-off from cartels, the subsequent extraction decisions of the competitive fringe could alter the market price paths of oil. Successful exploration might effectuate a supply shock that similarly lowers prices. In this case, the effects of reserve additions on the scarcity rent mimic the Pindyck model. As reserves increase, scarcity in the market decreases due to the negative relationship between reserves and extraction costs. As the costs of extraction decrease for a single supplier, that supplier extracts more and introduces an unexpected supply shock to the market. If producers in the competitive fringe consider individual, price-taking suppliers too small to alter market prices, then it is unlikely that the unexpected discoveries of a competitive producer affect the dynamic decision to extract.

The Pindyck and Salant and Henderson models lack several key determinants of the price and extraction path of nonrenewable resources, such as the effects of technology on extraction costs. Later studies improved the empirical performance of the Hotelling story by including adjustments that more realistically model nonrenewable resource production and its associated costs. Krautkraemer (1998) surveys this literature, where Hotelling pricing and production is adjusted for exploration, capital investment, and differences in ore quality. Although many of these factors affect nonrenewable resource prices and extraction rates, Krautkraemer notes the lack of convincing evidence of a particularly clear link between scarcity and price.

While the theoretical robustness of the Hotelling model in predicting price and extraction paths with given reserves is notably improved with the consideration of explanatory forces like exploration and technology, the proposition that the increasing scarcity of nonrenewable resources like fossil fuels is the primary determinant of fossil fuel price paths still lacks empirical support.[1] The early literature (1970-2000) on the price-extraction-scarcity story in nonrenewable resource markets struggled to find empirical support, and the rise in real oil prices in the years leading up to the Great Recession (2000 - 2008) seemed to signal the inevitable shift upwards in oil prices resulting in scarcity (see, for example, Hamilton (2008)). Subsequent declines in oil prices (2009 - 2017) suggest that the final realization of

[1] Livernois (2009) reviews this literature, concluding that "overall one cannot conclude that the Hotelling Rule has been a significant force governing the evolution of observed price paths for nonrenewable resources. It appears that other factors, notably technological change, revisions to expectations regarding the resource base, and market structure, have had a more significant influence on the evolution of prices."

Pindyck's U-shaped price path may be some years into the future.

I assume that Hotelling's Rule accurately describes the long-run relationship between global prices and supply-side scarcity. If developing countries hold unknown quantities of undiscovered resources, and have the most room for technological improvement in exploration, discovery, and recovery, then future oil extraction and prices will likely be influenced by reserve expansion in these developing countries. In the near-term, as in the recent past (1980-2015), reserve additions from these nations have likely been the result, and not the determinants, of price changes. Although scarcity and other supply-side factors certainly affect the price of oil, for the purposes of this paper, I assume that changes in prices mostly reflect other factors, including political events, cyclical demand, financial speculation, and price-setting behavior. I review the literature on some of other, empirically-demonstrated determinants of oil prices in the following sections.

3.2 Empirical Determinants of Global Oil Prices

The changes in oil prices, apart from economic recessions and political events, have remained fairly stationary (see Figure 6) since the 1970's. Prices have been noticeably more volatile since 2001. Oil prices peaked at $145 per barrel in July 2008, and fell to $30 per barrel just five months later. Although prices rebounded to above $100 for several years (March 2011 - July 2014), as of February 2017, prices have remained around or below $50 since December 2014. The Hotelling story, which assumes the price of oil increases with production, clearly does not explain sustained decreases in the price of oil. While scarcity might affect the price of oil in a competitive and efficient market, other events in the real global economic and political scene must complete the story. The increases, and subsequent decreases, in oil prices from 2005 to 2010 and from 2010 to 2015 resemble price changes from 1980 to 1985, and from 1990 to 1995 (see Figure 7). While the empirical literature has yet to validate Hotelling's rule for price and extraction paths of fossil fuels based on scarcity in the supply base, some studies have demonstrated that the demand-side, both in aggregate demand and oil-specific, "precautionary" demand, are key determinants of price shocks in the market for oil (Kilian, 2009); (Kilian and Hicks, 2013); (Juvenal and Petrella, 2015).

Kilian (2009) demonstrates empirically that shifts in the macroeconomic demand, as measured by dry cargo bulk freight rates, explain most of the economically significant price shifts from the 1980's through the 2000's. Kilian (2009) also finds that some of the variation in oil prices can be attributed to precautionary shifts in demand that are oil-specific, confined to the commodities market, and are unrelated to real scarcity. These precautionary shifts reflect fears about supply from news stories and political events and feedback from price changes in previous years. Killian similarly examines the effects of political events, particularly those in OPEC countries like the Iranian Revolution of the late 1970's and the Persian Gulf War in 1990, on the price of oil. He finds that supply shocks are indeed significant drivers of the price of oil, but much less important - and usually only significant in the very short-run - than other factors like aggregate demand, precautionary demand, and high-profile political turmoil. Baumeister and Kilian (2016) show the same to be true for the higher-magnitude drops in oil prices in 2014, using the same approach as Kilian (2009). Juvenal and Petrella (2015) find that behind shocks to real global demand, speculation in the oil market is most influential in determining the direction and magnitude of price changes. If speculators consider the Hotelling story a reasonable description of the future of oil prices, that is, that the price of oil will increase over time at a rate higher than the market interest rate, the demand for futures contracts will reflect speculative behavior in the oil market and drive prices for oil up.

In the long-run equilibrium of a competitive market, it is the general assumption that marginal costs are equal to prices, and where prices exceed marginal average costs, the marginal cost curve is essentially the supply (extraction) curve. In the case of nonrenewable resources, the Hotelling rule states that scarcity rents make the price slightly higher than the marginal cost curve in a competitive market because of foregone investments in the market and future increases in marginal costs due to scarcity.

However, the market for fossil fuels, and particularly for oil, is not a competitive market.

OPEC has repeatedly stated its intentions to keep real oil prices at or below a constant rate (as of 2016, \$50 per barrel), regardless of average extraction costs. With over three-quarters of the world's reserve base, and the majority of the world's oil production, OPEC can act as a single entity and set the price of oil by changing their flow of extraction to either mimic scarcity (slow down extraction) and increase prices, or mimic abundance (extract more) and decrease the prices of oil.

The coordinated efforts of OPEC to set prices further obscures the role of actual scarcity in setting prices. As Kilian (2009) and others note, political events in OPEC regions are particularly influential in determining oil prices. As suggested by Salant and Henderson (1978), were oil producers to take into account an unanticipated supply change (such as occurs in their case due to an "auction"), the extraction decisions of the "competitive fringe" would depend on the expected price of oil in future periods, including the risk of some "post-auction" price drop. The Salant-Henderson anticipations model would dictate that holding reserves is unprofitable when oil prices do not increase at a rate higher than the market interest rate. Clearly oil prices have not increased at a rate higher than the market interest rate, and thus far, there has been no mass sell-off of oil reserves from non-OPEC producers.

The natural resources literature has modeled the relationship between the supply of oil with reserve additions and price paths according to simple Hotelling dynamics, with poor empirical performance. Other effects, largely on the demand side, have better described historical changes in oil prices. Reviewing the literature, global oil prices can be described as some function of production (mainly in OPEC nations), global macroeconomic activity, speculative trends in the financial markets, and political turmoil in oil-producing countries. I will next review the literature on estimating potential reserves, and modeling reserves with oil market indicators, particularly the global price of oil.

Chapter 4

Modeling Reserve Additions

Estimating remaining extractable reserves is a complex task for both geologists and economists. Starting with M.K. Hubbert's 1956 prediction that oil extraction would peak in the 1970's and then decline,[1] a theory known as "peak oil," predictions of oil depletion have failed to describe observed oil production trends. Sorrell and Speirs (2010) survey the prevailing predictive techniques used to estimate total potential reserve accumulation, and conclude that continual revisions to peak oil predictions provide sizeable uncertainty in any estimate of ultimately recoverable reserves. Some recent studies (Murray and King (2012) and Chapman (2014), for example) have raised alarm that the peak oil turning point has come, citing the sharp increases in global prices from 2000 to 2008 as indicative of large-scale scarcity. Supply shocks like the North American shale oil boom suggest that fossil fuels are more abundant that previously thought, and that the global depletion of a resource of unknown abundance is difficult to predict.

The development of sophisticated drilling and extraction technology has facilitated the rise in oil production and substantial reserve accumulation. Managi et al. (2004) show that, despite increases in production, reserve additions outpaced production in the Gulf of Mexico from 1947 to 1996 due to dramatic decreases in the costs of exploration and reserve expansion

[1] As shown in Figure 5 oil extraction and reserve expansion has clearly not peaked.

from technological change. Further investment in petroleum resource management in many of the oil-producing developing countries will likely lead to more reserve additions as technology improves exploration success rates in new fields, and decreases the costs of reserve recovery in current fields. Steady annual increases in global production, independent of global demand and technology, positively affect extraction costs as scarcity makes extraction more difficult, but technology decreases the marginal costs over time, offsetting the increases in marginal costs due to scarcity.

In the absence of reliable predictions of the physical limits of fossil fuel reserves, I follow the assumption of Pindyck (1978) that, although fossil fuels are nonrenewable, they can be regarded as economically inexhaustible in the near-term. While Pindyck's U-shaped price path might explain the relationship between price paths and scarcity with rising marginal extraction costs, empirical studies have shown that prices have remained relatively unaffected, and reserve levels have steadily increased with extraction (see Chapter 3).

In fact, price changes are largely due to factors other than reserve expansion, especially for price-taking oil producers. While the Hotelling valuation of nonrenewable resources can be extended to include reserve additions in calculating potential price paths,[2] treating price shifts as exogenous in a model for reserve additions provides a more tractable description of marginal increases in the oil reserves of countries that are price-takers and have undiscovered reserves and underdeveloped technology. The econometric estimation of a reduced-form model of reserve additions as a function of historical prices, among other factors, becomes tractable when price changes are assumed to be exogenous. Empirical studies have found this approach to be more fruitful in empirically modeling reserve additions (Farzin, 2001); (Mohn and Osmundsen, 2008); (Ringlund et al., 2008); (Shafiee and Topal, 2009).

Several empirical studies have examined the upstream sector with models for exploration, drilling, and reserves as explained by prices, consumption, production, and exploration history. Farzin (2001) estimates the impact of price changes on reserve additions

[2] Pindyck (1978) and Krautkraemer (1998) model dynamic price and extraction paths with reserves in the United States, with little empirical support.

in the United States. His reduced-form model explains reserve additions based on reserves and prices in previous periods. He finds that increases in oil prices are significant determinants of reserve additions in following periods, with 10% lagged change in price explaining a 1% change in reserve additions (in tens of millions of barrels). Since his independent variables are simply lagged prices and reserves, Farzin's econometric model is useful for studying reserve additions in many empirical settings. Farzin derives his econometric model from the static unconstrained profit-maximization problem of a representative oil company. I review his theoretical approach in more detail in Chapter 5, and adopt a similar empirical model for explaining reserve additions.

Mohn and Osmundsen (2008) examine the effects of global oil price changes on exploration and discovery in a highly-developed, highly-regulated region of Northern Europe: the Norwegian Continental Shelf. Using time series on discovery (oil drilling activity), exploration, historical cumulative discovery, and oil prices, they estimate a positive relationship between successful exploration (discovery) and price changes between 1965 and 2004 across three regions of the Norwegian Continental Shelf. They distinguish three approaches to empirically studying exploration and discovery: (1) analyzing firm-specific data as a representation of industry-wide exploration behavior, (2) considering oil and gas field life-cycles across different geological zones, and (3) using aggregate exploration data across regional groups with no distinction for firms beyond the country or region under review. As Mohn and Osmundsen note, the third approach is the most common, and it is the approach they use. I, too, assume that aggregate national data can be used to describe the relationship between the level of reserves and global prices. If a national oil company (NOC) controls an entire region's oil operations, then that NOC acts as a single entity that makes the decision to explore. For regions that are partly owned by NOCs, international oil companies (IOCs) interested in the region must be permitted to explore in an NOC-controlled region. In countries without nationalized oil, national governments demand royalties and regulate oil exploration and production. In all cases, the decision-makers must consider both the costs and benefits of risky exploration efforts.

Ringlund et al. (2008) similarly assess the long-run price elasticities of exploration, but across different regions of the world with data on exploration. For non-OPEC Latin America, non-OPEC Middle East, and non-OPEC Africa (regions of particular interest to this study), Ringlund et al. show a long-run price elasticity of .8, .63, and .53, respectively. In the case of non-OPEC Latin America, for instance, their findings suggest a sustained annual 100% price increase in global oil prices will correspond to an 80% increase in oil rig activity. The price responsiveness of developing country price-takers predictably takes the same sign as OPEC and other developed countries, but differs in magnitude and speed of response. They attribute the quicker and larger price responsiveness in developed nations to the maturity of the oil fields, the presence of relatively unregulated, privatized international oil companies, and technology. In many developing countries, oil is nationalized and the oil fields are new in comparison. They use the Akaike Information Criterion to determine the optimal lag length on prices, and find that models including one and two-year lags on prices best explain exploration variation in non-OPEC Africa, Asia, and South America. They too base their empirical model on the model derived by Farzin (2001).

Shafiee and Topal (2009) construct a more simplified model for global reserves of oil, coal, and natural gas as explained by global prices and global consumption for each of the fuels being modeled. For oil, reserves are strongly associated with consumption,[3] at a high confidence level (99%). Without controlling for country heterogeneity, the estimated association between prices and reserves globally is negative. Although the estimated relationship between prices and reserves is statistically insignificant (60% probability of significance), the sign of the relationship is nonetheless surprising under the assumption that reserve changes do not affect prices. If reserve increases on a global scale do in fact cause prices to decrease (presumably due to a decrease in scarcity), then the model for reserves is

[3] The estimated coefficient on world oil consumption (billions of barrels) in a simple model of world proven oil reserves (billions of barrels) is 66.48. That is, controlling for price, their model suggests that per billion barrel increase in world consumption, world reserves increase by 66.48 billion barrels.

miss-specified and suffers from reverse causality. Shafiee and Topal assume no significant correlation between consumption and prices, and further assume these effects are not characterized by some unobserved heterogeneity across regions. The statistical insignificance of the estimation could alternatively reflect unaccounted variation in the political and economic structure of each country. The empirical model I specify differences away the unobserved heterogeneity across the countries in my sample with fixed effects.

Chapter 5

Empirical Model

This paper follows a stylized form of the empirical model introduced by Farzin (2001). Farzin assumes that a representative oil company is a profit-maximizing price-taker, and decides to expand reserves from period $t-1$ to t according to: $\max_{\Delta R_t^*} \Pi = P_t^e \times \Delta R_t^* - C^{\Delta R_t^*}$, where ΔR_t^* are the targeted reserve additions from exploration, P_t^e is the expected oil price (the marginal revenue from ΔR_t^*), and $C^{\Delta R_t^*}(\Delta R_t^*, R_{t-1}, Z_t)$ is the cost associated with adding ΔR_t^* reserves. He defines $C^{\Delta R_t^*}$ as a positive, nonlinear function of the targeted reserves as well as reserves in previous years (R_{t-1}) due to scarcity.[1] He also defines $C^{\Delta R_t^*}$ as a negative function of a time trend factor (Z_t) to reflect the cost-reducing technological improvements to exploration. Farzin uses adaptive expectations, modeling expected prices as a function of observed, lagged prices. He models targeted reserve additions with a standard partial adjustment process that includes observed, lagged reserve additions.

Log-transforming $P_t^e = MC^{\Delta R_t^*}$ from the first order conditions of the static[2] unconstrained profit-maximization problem, and solving for observed reserve additions, he

[1]Recall Pindyck's assumption that the cost of exploration is increasing with reserves in previous periods.

[2]Farzin (2001) and Mohn and Osmundsen (2008) justify analyzing the decision to explore as a period-by-period optimization problem on empirical and theoretical grounds. Pesaran (1990), for example, does not find evidence supporting present-discounted valuation in an empirical study on exploration efforts in the United Kingdom's Continential Shelf. Farzin (1986) estimates the discount rate of oil supplies to be much higher than the market interest interest rate (30%).

arrives at a model for reserve additions similar to the following:

$$ln\Delta R_t = \beta_0 + \beta_1 lnP_{t-1} + \beta_2 lnR_{t-1} + \beta_3 lnR_{t-2} + \beta_4 ln\Delta R_{t-1} + \beta_5 ln\Delta R_{t-2} + \beta_6 trend + e_t$$

Unlike Farzin, I do not attempt to construct a structural model for reserve additions, but rather aim to show the intuition behind estimating a linear reduced-form model of reserve additions with lagged reserves and lagged prices. Most importantly, prices in the current time period are unknown at the time of the exploration decision, and expectations are based on prices from previous years.

Following Farzin's assumption that a profit-maximizing firm is representative of all oil companies in a particular region, I treat regional reserve expansion as a simple economic decision based on the expected returns from additional reserves, and the expected costs associated with adding reserves. Modeling reserve additions across entire regions or countries is common in the empirical literature. Regarding exploration activity, Mohn and Osmundsen (2008) note, "the most common perspective is based on aggregate data for regions, countries or groups of countries." In reality, reserve additions are the result of economic decisions made by numerous oil companies operating in a particular region or country. IOCs, owned by private and public investors, are profit-maximizing firms, and compete with other IOCs and NOCs in the same region. When an NOC controls the production of oil in a country, the entire country acts more or less as an individual price-taking producer in the global market for oil. Reserve expansion then follows a decision to search for oil in new areas or in already-discovered fields. Success in ensuing exploration efforts results in larger known accumulated reserves. The empirical model presented in Chapter 6 reflects this simple view of profit-maximization behavior.

Because proved reserves are extracted or fully prepared for extraction within five years of their classification (SPE and AAPG, 2007), the prices are predicted for five years following the decision to explore ($n + 5$ where n is the period of exploration), and four years following the reported addition of the reserve ($t + 4$ where t is the period of reserve classification). For clarity, I use $t - 1$ to refer to the period of exploration, t to refer to the period of reserve classification, and $t + 4$ to refer to the period of extraction throughout the paper. Figure 8 shows a simplified chart of the decision to explore for reserves based on the total expected costs and expected revenue associated with additional reserves.

The costs associated with valuable reserve additions consist of the cost of exploration (assumed to be known at the period of exploration) and the costs of extraction (assumed to be unknown at the period of exploration). If each discovery increases the difficulty of additional discovery due to scarcity, then the costs of successful exploration can be described as a positive and increasing function of reserves at the period of exploration. As new oil fields are discovered in a region, the costs of discovering more fields (the costs of exploration) increase because there remain fewer fields to discover. Since extraction and reserves in future periods are unknown when the exploration decision is made, the costs of extraction can only be assumed to decrease over time with technological change, and vary across countries with different geographical, economic, and political characteristics.

For a firm to explore, the expected price must exceed the combined expected marginal cost of exploration and extraction. A firm can know with certainty that scarcity makes future discovery costlier, but might not know if discovering new oil fields will decrease or increase the marginal costs of extraction at a rate that will change the relationship between the total marginal costs of adding reserves. Technological improvements to geological assessment and drilling facilitate discovery and extraction, decreasing the costs associated with profitable reserve expansion. The decision to explore is made when the expected marginal revenue (expected oil price) from the extracted resource increases, or when the marginal costs of exploration and extraction decrease as technology improves with time. In the following chapter, I incorporate this logic into an empirical model similar to that of Farzin (2001), with the additional consideration of oil nationalization.

Chapter 6

Data, Methods, and Empirical Specification

To estimate the parameters of the reduced-form econometric model I specify below, I use a time series on global oil prices, and balanced panel data on the estimated proved reserves across a sample of non-OPEC, non-OECD countries. These countries are listed in Table 1. Descriptive statistics on these data are found in Table 2. The sample data, collected from the U.S. Energy Information Administration's International Oil Production data set, include the estimated proved oil reserves of 24 countries from 1980 to 2015[1], as published in the *Oil & Gas Journal*.[2] I also include indicator variables for oil nationalization based on information primarily gathered from national oil company websites.

The importance of data quality in studying national energy indicators cannot be understated, and is likely one of the reasons few empirical studies on exploration and reserve development in developing countries have appeared in the energy and resource literature. This

[1]Because two-year reserve lags are included as independent variables, the data for year 1980 and 1981 are missing, so the panel data spans 34 years (1982 to 2015), rather than 36 years.

[2]December 7, 2015 *OGJ* publication: "The published reserves figures rely on survey responses and official updates by individual countries, which are not provided every year in many cases. *OGJ* changes its estimate for a particular country only when it receives evidence that a change is in order." I have removed countries where data is missing.

paper models the economic decision to expand the current reserve base by searching for oil in new and existing oil fields. Direct data on exploration, drilling, and discovery are difficult to obtain, especially for developing countries with limited resources and nationalized oil fields. Proved reserves data, while widely available, are estimates, and lack the precision and transparency of other data prevalent in developed and OPEC countries. The literature on exploration and drilling has primarily focused on developed regions with higher-quality data. The quality of the data for developed and OPEC regions enables some of these studies to separate reserve changes according to the means of reserve expansion (exploration, extensions, and revision).

Several differences between the countries used in this study (non-OECD, non-OPEC) and other, data-rich countries account for disparity in data availability and quality. International agreements, like climate coalitions and OPEC membership, for instance, demand a certain level of transparency. The overall regulatory atmosphere and political structure of developed countries like Norway (Mohn and Osmundsen, 2008) and the United States (Ringlund et al., 2008), also differs immensely from that of developing countries. Despite the limitations to the sample data in this study, the use of panel data spanning different countries improves on regional estimations, where observed changes in reserves may be due to unobserved, country-specific effects. Differencing away the country fixed effects should improve on this. The results from this study can then be compared to the results of other regional and global studies discussed in Chapter 4.

The dependent variable $\Delta ln(R_{it})$ in my analysis is the percent change in reserves following the exploration decision. I specify the following reduced-form equation for the baseline model:

$$\Delta ln(R_{it}) = \quad \alpha + \phi ln(P^e_{t+4}) + \eta ln(R_{it-2}) + \delta_1 NAT1_{it} + \delta_2 NAT2_{it} + \tau trend_t + u_i + \epsilon_{it}$$

The expected prices in the period of extraction, $ln(P^e_{t+4})$, represent the marginal revenue from additional reserves when production begins. Oil prices follow a strong AR(1) process. For the series P from 1975 to 2015, where $P_t = \alpha + \rho P_{t-1} + e_t$, ρ is estimated by OLS to be $\hat{\rho} = 0.89$.[3] To calculate P^e_{t+4}, I use the multiple-step-ahead forecasting method for an AR(1) process presented by Wooldridge (2015): $E[P_{t+4}|P_{t-1}] = (1 + \rho + \rho^2 + \rho^3 + \rho^4)\alpha + \rho^5 P_{t-1}$, estimated as $\hat{f}_{t,5} = (1 + \hat{\rho} + \hat{\rho}^2 + \hat{\rho}^3 + \hat{\rho}^4)\hat{\alpha} + \hat{\rho}^5 y_t$.[4] Because the expected price of oil in the period of extraction represents the marginal revenue from additional reserves, the sign on expected prices, ϕ, is expected to be positive.

Without information on the costs associated with exploration, reserves in previous years, $ln(R_{it-2})$, are used to control for exploration costs.[5] Since higher reserves per unit area indicate increasing scarcity and therefore increasing costs of exploration (again, an assumption from Pindyck (1978)), the coefficient on two-year lagged reserves, η, is expected to be negative.

The national government's involvement in oil exploration and production decisions varies across countries, and sometimes across years. To control for the effects of nationalization on the exploration decision, the empirical model includes two time-varying indicator variables for oil nationalization. A categorical variable NAT, which takes on values 0, 1, or 2, indicates the extent to which a country's hydrocarbon resources are owned and operated by the state in a given year. I categorize countries without nationalized oil, or with little public investment in national oil as $NAT = 0$. Most of these countries receive royalties from IOCs who extract in their territory. These countries generally have government agencies, like Morocco's National Office of Hydrocarbons and Mining, or Guatemala's Ministry of Energy and Mines, that regulate the oil industry, but they do not house large-scale national oil companies. I use

[3] See Table 9 for autoregression results.

[4] Using simple lagged prices (P_{t-1}) for expected prices in the period of extraction instead of forecasted prices does not notably alter the estimation results. Alternative formations of price expectations are briefly discussed in Chapter 8.

[5] $ln(R_{it-2})$ is used instead of $ln(R_{it-1})$ since the dependent variable, $\Delta ln(R_{it}) = ln(R_{it}) - ln(R_{it-1})$, includes R_{it-1}. Using R_{it-1} to control for lagged reserves does not qualitatively alter the estimation results of the baseline model.

$NAT = 1$ for countries that have a strong and vested state presence in their national oil resources, but still allow and encourage foreign involvement. The governments of these countries are generally primary shareholders of publicly traded oil companies, and even allow smaller, privately-owned companies to operate. Examples include India's IndianOil[6], and, starting in the late 1990's, Brazil's PetroBras and China's PetroChina. In some countries, like Peru and Malaysia, the government either controls all of the oil in the country, or the overwhelming majority. These countries are categorized as $NAT = 2$.

I allow NAT to vary across time, primarily in the event of a publicized change in private or public control of oil resources and operations. Such was the case for the privatization of Argentinian oil and gas in 1993, and the subsequent re-nationalization in 2011. Since large IOCs, like Shell, BP, Chevron, and ExxonMobil, are among the largest corporations in world by market capitalization, they likely have more readily available capital for investments in risky exploratory efforts, especially when compared to much smaller NOCs. NAT enters the model as two indicator variables $NAT1_{it}$ for $NAT = 1$, and $NAT2_{it}$ for $NAT = 2$. I expect the coefficients on nationalization, δ_1 and δ_2, to be negative.

The total costs associated with adding reserves include the costs of exploration, which the firm realizes in the period of the exploration decision, and the costs of extraction, which the firm realizes in the period of extraction but does not know with certainty prior to making the decision to explore. Without explicit information on the costs of extraction, the remaining control variables, which include a trend variable, $trend_t$, and fixed-effects indicator variables for each country u_i, control for the differences in extraction costs across reserve time periods and the fixed differences in extraction costs across countries. $trend_t$ controls for cost-reducing changes in technology over time and should be positively associated with reserve changes. u_i, which controls for time-invariant, country-specific fixed effects, will be differenced away in fixed effects estimation.

[6] According to Shareholding Pattern reports from IndianOil, from 2012 to 2015, the Indian government owned between 60% and 80% of IndianOil, the country's largest oil producer. IndianOil has domestic competitors, but they are much smaller publicly- and privately-owned companies.

The baseline model explains the changes in proved reserves immediately following the period of exploration as a reduced-form equation of variables that control for the expected revenue and costs associated with adding reserves. The model also controls for the fixed effects of individual countries in the sample and oil nationalization. I estimate the model with OLS fixed effects, and OLS random effects and pooled OLS estimation. To address heteroskedasticity and serial correlation in the model, I use robust standard errors calculated according to Arellano (1987). I present and discuss the results of the OLS fixed effects, and discuss some alternative specifications and their results, in Chapter 7.

Chapter 7

Results

I estimate the baseline reduced-form model by OLS fixed effects, OLS random effects, and pooled OLS estimation. The results are detailed in Table 3. Where significant, the estimated coefficients vary in magnitude, but not in sign across estimation methods. The model utility test shows that the model explains much of the variation in reserve changes when estimated with OLS fixed effects. I review the coefficient estimates from the fixed effects estimation, and discuss their statistical and economic significance.

The literature, in agreement with economic intuition, suggests that increases in expected oil prices provide incentive to search for more oil in each period. The empirical results of this study do not support this claim. In contrast to the hypothesized positive effect of prices on reserve changes, the estimated effect of prices on reserve changes is negative, but small and statistically insignificant.[1] Using prices in previous periods to predict the price in the period of future extraction, the price-taking firm makes the decision to explore with marginal revenue based on price expectations.[2] Increases in prices are often reflective of an unpredictable shock

[1]Note that random measurement error in the forecasted price variables biases the standard error on $\hat{\phi}$ downward. As shown in Table 3, $\hat{\phi}$ is statistically insignificant with robust standard errors. Thus, the robust standard errors on $\hat{\phi}$ in Table 3 are understated, which in turn strengthens the finding that price effects are insignificant.

[2]It is well known that oil prices are volatile (see Figure 7 and Table 2). The firm will likely under- or overestimate the returns on reserve addition since price expectations can only be made based on a previous year's prices, and price expectations are rarely the same as realized market prices. I discuss how price expectations are formed briefly in Chapter 6.

to the macroeconomy, a recently introduced policy, or cartel behavior, making the accurate prediction of prices years into the future a difficult task for the firm.[3] In the presence of other factors that can be known with a greater level of certainty, like the costs of exploration, reserve additions could be unresponsive to prices due to the difficulty of predicting volatile oil prices years into the future. If a firm follows the Hotelling story, even qualified for technology gains, then prices will likely increase substantially at some time in the future due to scarcity. Four-period-ahead price predictions would therefore do little to capture dynamic profit-maximization in the context of this model.

The model captures exploration cost estimates with reserves in previous years with $ln(R_{it-2})$. Reserves in previous periods should increase the cost of adding reserves as reserves become harder to find due to scarcity. R_{it-2} is a stock variable that accumulates over time with reserve additions, due to exploration. The coefficient estimate on $ln(R_{it-2})$ is unsurprisingly negative, and statistically significant at the 99% confidence level. The estimation results suggest that an increase of 10% in reserves in previous periods would decrease the percent change in reserve additions in the current period by 1.5%. This supports the notion that firms cost-minimize on exploration in the decision to explore, or at least reflects the fact that as reserve levels increase, the percent change in additions will be smaller.

The categorical variable on nationalization enters the model as two indicator variables, one for weak nationalization ($NAT1_{it} = 1$ when $NAT_{it} = 1$), and one for strong nationalization ($NAT2_{it} = 1$ when $NAT_{it} = 2$), with no oil nationalization ($NAT_{it} = 0$) as the reference. The estimated association between oil nationalization and reserve additions is negative and statistically significant at the 95% confidence level for both indicator variables. A stronger government presence is associated with decreases in the percent change in oil reserves. Specifically, the presence of "weak nationalization" is associated with an 8% decrease in reserve additions compared to countries without nationalized oil. "Strong nationalization"

[3]The literature on oil price determinants has shown that demand-side shocks, speculation, and cartel behavior, rather than scarcity, have been the most significant determinants of shifts in oil prices (Kilian, 2009)(Kilian and Hicks, 2013)(Livernois, 2009). Given the increasing accumulation of reserves (see Figures 9 and 10), and the shifts in oil price due to macroeconomic events (see Figure 6), this makes sense.

is associated with a 15% decrease in reserve additions. As discussed briefly in Chapter 6, IOCs are more likely to invest in exploration efforts given their large market capitalization and international presence. Ringlund et al. (2008) also found it to be the case that in countries where IOCs dominate (most oil-producing, developed countries), reserves are added at a faster pace and respond more quickly to changes in prices.

Extraction costs, which are unobserved in the model, are captured by the *trend* variable and the u_i indicators for country fixed effects. The effect of technology on reserves as measured by the $trend_t$ variable is very small and statistically insignificant. As noted above, an F-test shows the fixed effects are jointly significant determinants of reserve additions. The significance and magnitude of several of the coefficient estimates change from OLS random effects and pooled OLS when fixed effects are included in the model. For cultural, political, geographical, and economic reasons, oil reserves and reserve additions differ across global regions.

As such, the estimation results support the claim that firms are cost-minimizers, and that the presence of international oil companies increases successful exploration activity. According to the empirical model, the cost of exploration as measured by information available at the time of exploration, and the government's presence in the oil industry as measured by indicator variables for oil nationalization, are apparent determinants of reserve additions.

The exogeneity in the independent price variables of the econometric model depends in part on the price-taking characteristic of the countries in the sample, and alludes to previous empirical studies on the exogeneity of shifts in oil prices (notably, Kilian (2009)). Nevertheless, endogeneity is an obvious concern in this study, despite my efforts to argue otherwise. Simultaneity could be present in the actual structure of the reserve development process. Unobserved variables could have also have simultaneous effects on price changes and reserve additions. Furthermore, although strict exogeneity is assumed in my sample and for the population under review (non-OPEC, non-OECD countries), reserve additions could influence prices in the future. To address endogeneity concerns associated with price predictions, I estimate the baseline model by 2SLS where two and three-year lags of world GDP growth are used as instrumental variables for price predictions. The 2SLS fixed effects estimation of the baseline model is also presented in Table 3, column 4. The estimated coefficients on the exogenous independent variables remain fairly unchanged in 2SLS. The estimated coefficient on predicted price becomes positive, but is very statistically insignificant.

The objective of the present study is to find the determinants of proved reserves in developing countries, with a model that controls for heterogeneity across countries. While assuming the exogeneity of oil prices assists in conducting empirical estimation of the effect of oil prices on reserve additions, reserve additions from developing countries will eventually influence prices with the effects of scarcity, and the value of adding additional reserves will approach zero. According to Pindyck (1978), exploration and extraction of oil will expand until the supply base is economically unprofitable to maintain, or until the demand for a substitute fuel successfully replaces crude oil. As demonstrated by the empirical results of this study, the costs associated with reserves, which are more easily estimated than revenues from volatile oil prices, seem to be key determinants of reserve additions. Oil nationalization also significantly affects reserve additions.

I estimate several alternative specifications to test the robustness of the baseline model estimation to changes in the model specifications. Each alternative model is listed in Chapter 8, and the results for each alternative specification are detailed in tables in the appendix. The estimated coefficients on each explanatory variable do not differ significantly across estimated models.

Chapter 8

Alternative Specifications

To test the robustness of the estimation results on the baseline model, I specify and estimate several alternative models. These alternative specifications introduce changes to the control variables for price expectations and nationalization, and include other factors that could influence exploration decisions and discovery. The estimation results are listed in Tables 4, 5, 6, 7, and 8.

Firms vary in their response time to price changes, and in their decision to search for and classify their discoveries as proved reserves.[1] To check the robustness of my estimation results to changes in the formulation of price expectations, I specify ad-hoc price expectations for period t as the geometric mean of the previous four year time periods in the first alternative model: $P^e_{t+4} = \left[P^{\rho_1}_{t-1} \times P^{\rho_2}_{t-2} \times P^{\rho_3}_{t-3} \times P^{\rho_4}_{t-4}\right]^{\frac{1}{\rho_1+\rho_2+\rho_3+\rho_4}}$. Log transformed, this becomes $ln(P^e_{t+4}) = \frac{ln(P_{t-1})\rho_1+ln(P_{t-2})\rho_2+ln(P_{t-3})\rho_3+ln(P_{t-4})\rho_4}{\rho_1+\rho_2+\rho_3+\rho_4}$. The ρ parameters represent the "elasticity of price expectations" to nearer-term prices. Increasing the number of years beyond four year's time does not significantly change the estimation results of the reduced form model. The coefficient estimates on each of the price parameters enter the model as:

[1] Ringlund et al. (2008) use monthly price data and price-smoothing, nonlinear functions to represent the coefficient on price in their model.

$$\begin{aligned}\Delta ln(R_{it}) = \quad & \alpha + \boldsymbol{\phi_1 ln(P_{t-1}) + \phi_2 ln(P_{t-2}) + \phi_3 ln(P_{t-3}) + \phi_4 ln(P_{t-4})} + \eta ln(R_{it-2}) \\ & + \delta_1 NAT1_{it} + \delta_2 NAT2_{it} + \tau trend_t + u_i + \epsilon_{it}\end{aligned} \tag{8.1}$$

As shown in column 1 of Table 4, the signs on lagged prices alternate in sign, but are only significant and *negative* for two-year lags of prices. The alternating signs likely signify that, where firms explore in response to changes in price, an adjustment process characterizes their response to price changes across years.

I also specify a model that includes the simple arithmetic mean of four years of price lags. Where $\bar{P_{lag}} = \frac{(P_{t-1}+P_{t-2}+P_{t-3}+P_{t-4})}{4}$, the model takes the following form:

$$\Delta ln(R_{it}) = \quad \alpha + \boldsymbol{\phi ln(\bar{P_{lag}})} + \eta ln(R_{it-2}) + \delta_1 NAT1_{it} + \delta_2 NAT2_{it} + \tau trend_t + u_i + \epsilon_{it} \tag{8.2}$$

The results from this second alternate model are also listed in Table 4, in column 2. The sign on average lagged prices is surprisingly negative, but not statistically significant.

Recall that proved reserves are discovered reservoirs of oil that have at least a 90% probability of being extracted "*under current economic and operating conditions*" (that is, given the current price of oil and the current cost of extraction). Proved reserves are some function of the reserves of the previous time period adjusted for the price of oil at the current time period, plus actual additions from exploration and drilling. As the definition of proved reserves suggests, some portion of the increase (decrease) in proved reserves across time periods is simply an adjustment of previous-year estimates with updated increases (decreases) in global prices. In following specification, the difference in logged price lags, $\Delta ln(P_{t-1})$, controls for reserve revisions due to changes in prices rather than actual reserve additions.

$$\Delta ln(R_{it}) = \quad \alpha + \phi ln(P^e_{t+4}) + \eta ln(R_{it-2}) + \boldsymbol{\zeta \Delta ln(P_{t-1})} + \tau trend_t + u_i + \epsilon_{it} \tag{8.3}$$

As shown in column 3 of Table 4, the coefficient estimate on $\Delta ln(P_{t-1})$, $\hat{\zeta}$, is unsurprisingly positive. A 10% increase in prices is associated with a 0.6% increase in reserve additions in the following period.

The baseline model assumes that the expected price of oil at the period of extraction is a simple function of lagged annual average oil prices ($P^e_{t+4} = f(P_{t-1})$). In the days, weeks, and months leading up to the exploration decision, firms observe daily spot crude oil prices, which vary significantly. The economic information available to firms at the time of the exploration decision includes the variance of prices in a given period, a moment of the oil price time series that could cause uncertainty and discourage risk-averse firms to engage in exploration. To account for the volatility of prices, I include a variable for variance, $\sigma^2_{P_t}$, which is the variance in the annual price of oil across months.

$$\Delta ln(R_{it}) = \quad \alpha + \phi ln(P^e_{t+4}) + \eta ln(R_{it-2}) + \boldsymbol{\phi_\sigma \sigma^2_{P_t}} + \tau trend_t + u_i + \epsilon_{it} \tag{8.4}$$

These results are shown in column 4 of Table 4. The coefficient estimate on monthly price variance is small and statistically insignificant.

In an additional specification, a single variable controls for the presence of international oil companies in a country.

$$\Delta ln(R_{it}) = \quad \alpha + \phi ln(P^e_{t+4}) + \eta ln(R_{it-2}) + \boldsymbol{\delta IOC_{it}} + \tau trend_t + u_i + \epsilon_{it} \tag{8.5}$$

As seen in column 1 of Table 5, the coefficient estimate on IOC is positive and significant. The sign, size, and significance of the coefficient on IOC is consistent with the estimated negative NAT terms in the baseline model.

I introduce an interaction term between IOC and P^e_{t+4} to control for the difference in price responsiveness when oil companies operate in an oil-producing country. This model's estimation results are presented in column 2 of Table 5.

$$\begin{aligned}\Delta ln(R_{it}) = \quad & \alpha + \phi ln(P^e_{t+4}) + \eta ln(R_{it-2}) + \boldsymbol{\delta IOC_{it} + \gamma IOC_{it} * ln(P^e_{t+4})} \\ & + \tau trend_t + u_i + \epsilon_{it}\end{aligned} \tag{8.6}$$

The coefficient estimates on forecasted prices and international oil companies are statistically insignificant. The coefficient on IOC increases after controlling for the differences in price responsiveness, but is statistically insignificant.

While the fixed effects account for fixed, time-invariant differences across countries, scaling reserves by land area further scales reserves in both the dependent variable and the the lagged reserves independent variable by the total area of the country in which the reserves are located. In the following model, reserves are scaled by land and water area to account for differences in reserve changes due to geographical differences. Where $\widetilde{R}_i = \frac{R_i}{area_i}$, the model takes the following form:

$$\boldsymbol{\Delta ln(\widetilde{R}_{it})} = \quad \alpha + \phi ln(P^e_{t+4}) + \boldsymbol{\eta ln(\widetilde{R}_{it-2})} + \delta_1 NAT1_{it} + \delta_2 NAT2_{it} + \tau trend_t + u_i + \epsilon_{it} \tag{8.7}$$

The estimations, listed in Table 6, remain similar to those of the baseline model.

I lastly introduce variables for governance to control for differences in political climates across time periods and countries. Where gov_{it} is the time-varying global ranking of each country in the sample for the Government Effectiveness indicator of the World Bank's Worldwide Governance Indicators project,[2] the model takes the following form:

[2]Data from the Worldwide Governance Indicators project span from 1996 to 2016. Models 8.7 and 8.8 are estimated for years 1996 to 2015.

$$\begin{aligned}\Delta ln(R_{it}) = \quad & \alpha + \phi ln(P^e_{t+4}) + \eta ln(R_{it-2}) + \delta_1 NAT1_{it} + \delta_2 NAT2_{it} + \\ & \boldsymbol{\beta_{gov} gov_{it}} + \tau trend_t + u_i + \epsilon_{it}\end{aligned} \tag{8.8}$$

Where pol_{it} is the time-varying global ranking of each country in the sample for the Political Stability indicator of the World Bank's Worldwide Governance Indicators project, the model takes the following form:

$$\begin{aligned}\Delta ln(R_{it}) = \quad & \alpha + \phi ln(P^e_{t+4}) + \eta ln(R_{it-2}) + \delta_1 NAT1_{it} + \delta_2 NAT2_{it} + \\ & \boldsymbol{\beta_{pol} pol_{it}} + \tau trend_t + u_i + \epsilon_{it}\end{aligned} \tag{8.9}$$

The estimation results on the models 8.7 and 8.8 are listed in Table 7. In both cases, governance indicators do little to explain reserve additions. The differences in the political and legal structure of each country is likely sufficiently captured by the fixed effects and oil nationalization indicator variables.

As a final robustness check, I remove explanatory variables from the baseline model through backwards selection. These stepwise results are presented in Table 8. When *trend* is removed, the estimates on lagged reserves and nationalization are similar to those of the baseline in magnitude and sign. When nationalization is removed, the estimated coefficient on lagged reserves does not change significantly. Price predictions are only significant when they are the only explanatory variables for reserve additions.

Chapter 9

Discussion and Conclusion

Among numerous economic motivations for examining the (pre-)production and price of fossil fuels, the pressing and largely unresolved global economic problem of climate change invites further investigation. Economists, along with the entire scientific community, estimate that the costly damages of permanent, global climate change largely outweigh costs of mitigation in terms of economic growth and transaction costs (Pachauri et al., 2014); (Stern, 2007). Global cooperation is required to successfully reach non-catastrophic levels of atmospheric GHGs (around 550 CO_2-equivalent particles per million), and it is well known that free-riding is the largest obstacle to universal and effective global climate change policy. To mitigate emissions, many wealthy countries form international environmental agreements (IEAs) focused on reducing emissions with price and quantity controls in regional fossil fuel markets.

Regional cost-benefit analyses with complex, structural dynamic integrated assessment models are often used to set emissions targets restricting regional consumption of fossil fuels. As demand decreases due to international restrictions on climate-cooperating nations, the price of globally traded fossil fuels (petroleum in particular) decreases, making fossil fuels more economical for consumers in non-mitigating countries. With rapidly growing populations and economies, non-mitigating regions benefit from global reductions of other, wealthier regions, and in many cases are encouraged to emit more. Even if a non-mitigating nation considers the environmental impact of fossil fuel emissions, the decrease in the emissions of climate-cooperating nations makes the environmental damage from additional emissions less costly compared to the "business-as-usual" scenario if global emissions decrease overall. The increase in emissions in non-mitigating regions as a result of well-intentioned regional climate regulations, known as leakage, has troubled climate economists for decades. The literature on free-riding, and effective policy in the presence of free-riding, is fairly pessimistic under the current and foreseeable state of international climate policy (see, for example, Rogelj et al. (2016)).

Climate concerns have begun to accelerate the transition to cleaner, renewable sources of energy, but fossil fuels will nonetheless continue to play an important role in the development of future economies and populations. Developing countries in Asia, Africa, and South America, not historically cooperative in global climate agreements, will likely increase their production and consumption of fossil fuels in coming years as other climate agreement signatories decrease theirs. In the context of climate change and international mitigation efforts, the question arises: do international climate agreements, characterized by regional and global taxes, affect the exploration and extraction decisions in non-mitigating, price-taking countries?

With this question in mind, Berg et al. (2002) form a Nash-Cournot model[1] for extraction in the "competitive fringe" of global oil producers (non-OPEC countries) that includes exploration. They introduce a regional carbon tax in OECD countries in a simulation model of extraction and exploration, with the standard assumption that the costs of extraction are increasing with extraction and decreasing with exploration, and that the costs of exploration are increasing with exploration. If prices decrease in the market due to a carbon tax, the short-run incentive to produce oil decreases. When the price drops below the marginal cost of production, the incentive to extract disappears entirely. The increase in prices over time gives a dynamic incentive to delay production until prices increase.

[1]Salant (1976) first introduced the Nash-Cournot model for the oil market with a competitive fringe. The Nash-Cournot model is characterized by the assumption that each producer maximizes profits while taking into account the sales of the other producers.

The qualified Hotelling rule would dictate that the price increases at the market interest rate, plus some scarcity rent. A regional carbon tax simply slows down the increase in prices over time, still giving price-takers an incentive to delay production, while decreasing the short-run incentive to produce. If the oil producer follows the dynamic Hotelling story, then the carbon tax will cause both the short-run and dynamic effects on decision to extract and explore for oil. The Berg et al. (2002) simulation results suggest that a carbon tax has negligible effects on production and exploration in non-mitigating countries (non-OECD, non-OPEC), and only slightly brings the period of increased extraction closer to the present. This is likely because a decrease in the global demand and global price in the present period due to a regional carbon tax would not be sufficient to cause a forward-looking (and optimistic) producer to deviate from its original exploration and extraction path. While the effects of climate agreements on oil exploration and extraction in non-mitigating, price-taking countries remain to be seen, this study's estimated, insignificant relationship between reserves and prices, in agreement with the Berg et al. (2002) simulation results, suggest that short-term price changes are negligible in the decision to explore.

Considering the importance of energy, the environment, and the economy, the question arises: how do changes in prices influence fossil fuel exploration? The results from an empirical study on price-taking developing countries suggest that nationalization and reserves at the time of the exploration decision are key determinants of proved oil reserve additions. The relationship between changes in the price of oil and reserve additions is less clear, but an estimated model for reserve additions suggests that the costs associated with exploration are more important factors in the decision to explore.

As the developed world turns to cleaner, renewable sources of energy because of environmental and energy security concerns, there remain concerns over the production and consumption of fossil fuels in developing countries with growing economies. Estimating a model for reserve additions, I find little evidence to suggest that reserve additions are responsive to changes in prices. This could be due to the difficulty of predicting oil prices in years prior to extraction and production. It is likely that, if firms consider oil prices when deciding to explore, they do so dynamically and consider exploration and extraction costs as the primary factors in their decision to add reserves.

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APPENDICES

Graphs and Charts

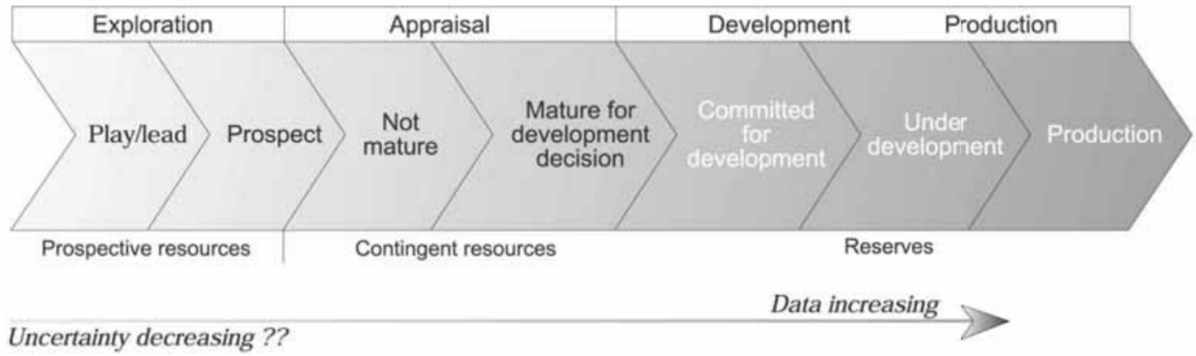


Figure 1: Reserve Development Process

(Wim et al., 2001)

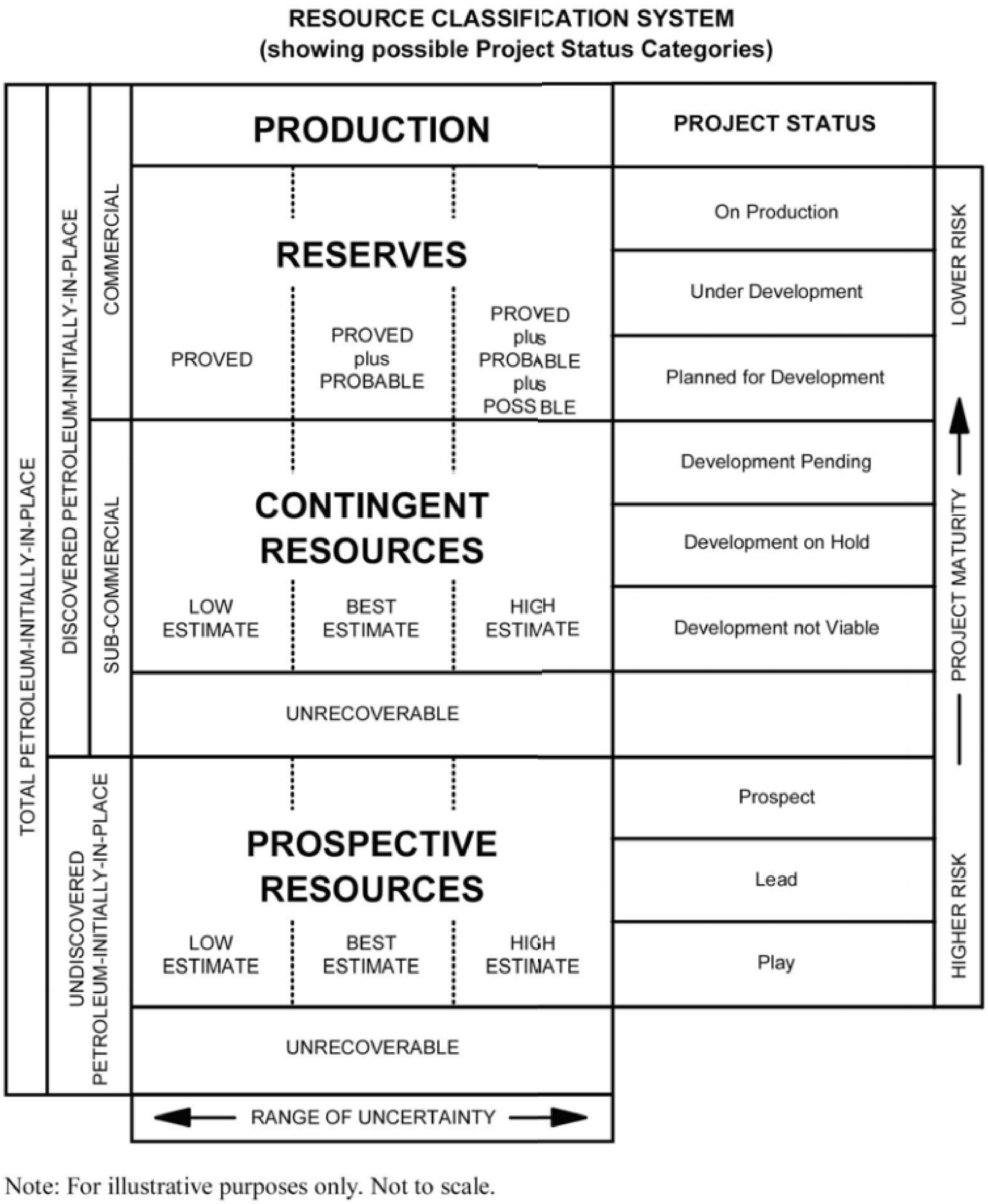


Figure 3: Resource Classification

(Wim et al., 2001)

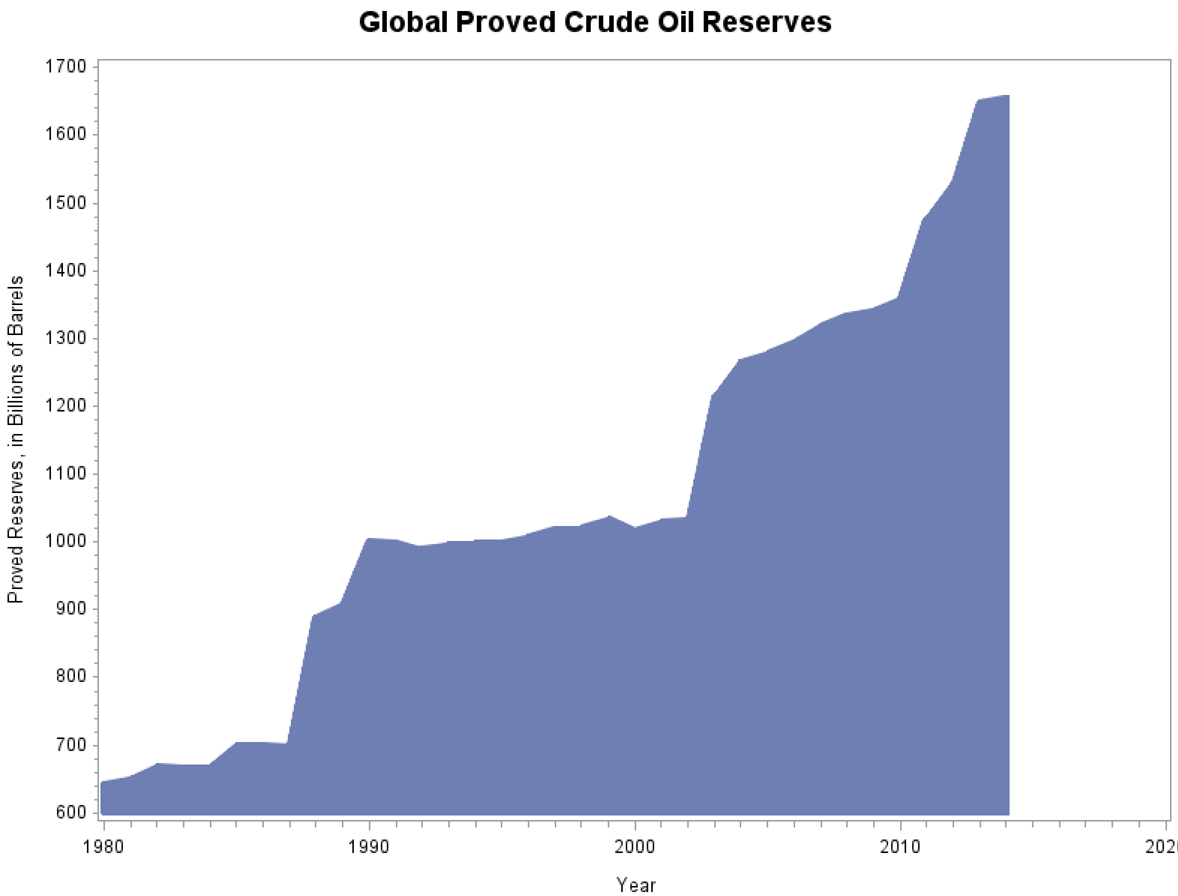
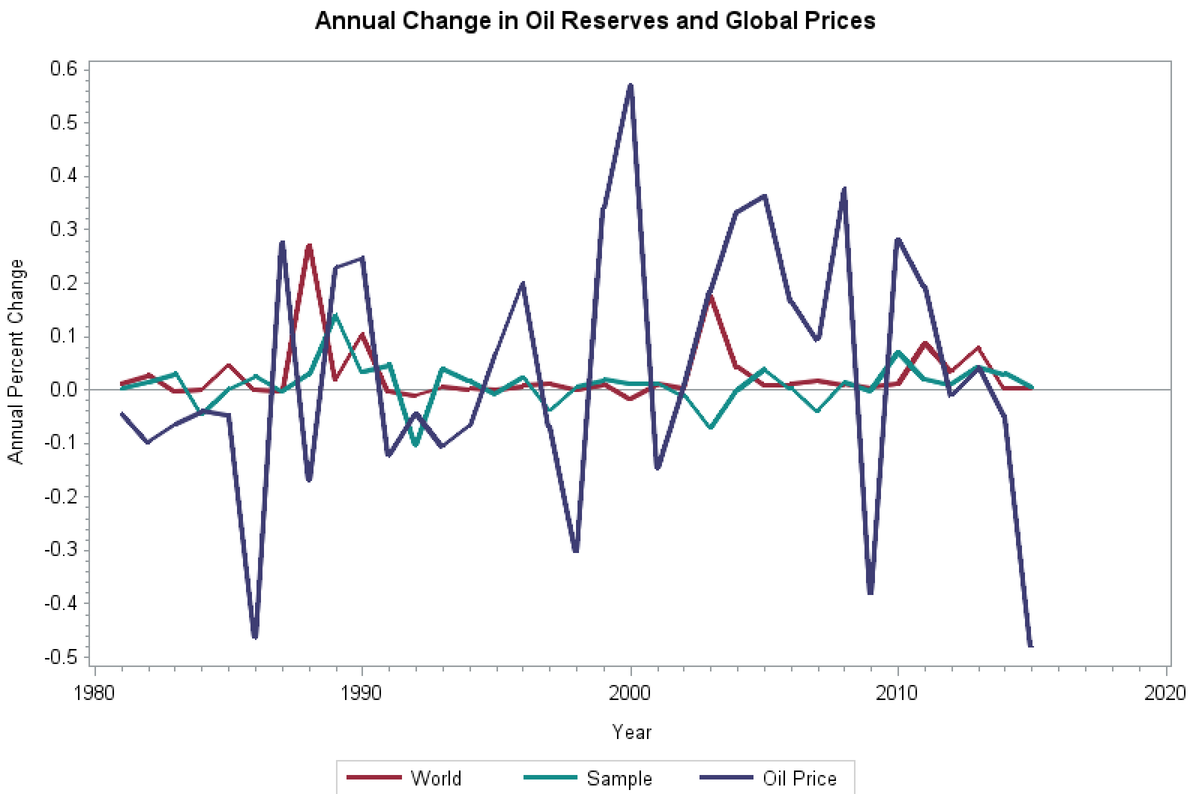


Figure 5: Estimated Global Proved Crude Oil Reserves, 1980 - 2015



Source: United States Energy Information Administration

Sample Countries: Argentina, Bahrain, Barbados, Bolivia, Brazil, Cameroon, China, Colombia, Congo (Brazzaville), Congo (Kinshasa), Egypt, Ghana, Guatemala, India, Indonesia, Malaysia, Morocco, Oman, Pakistan, Peru, The Philippines, Syria, Taiwan, Thailand, Trinidad, Tunisia

Figure 6: Annual Change in Estimated Proved Oil Reserves and Global Crude Oil Prices, 1980 - 2015

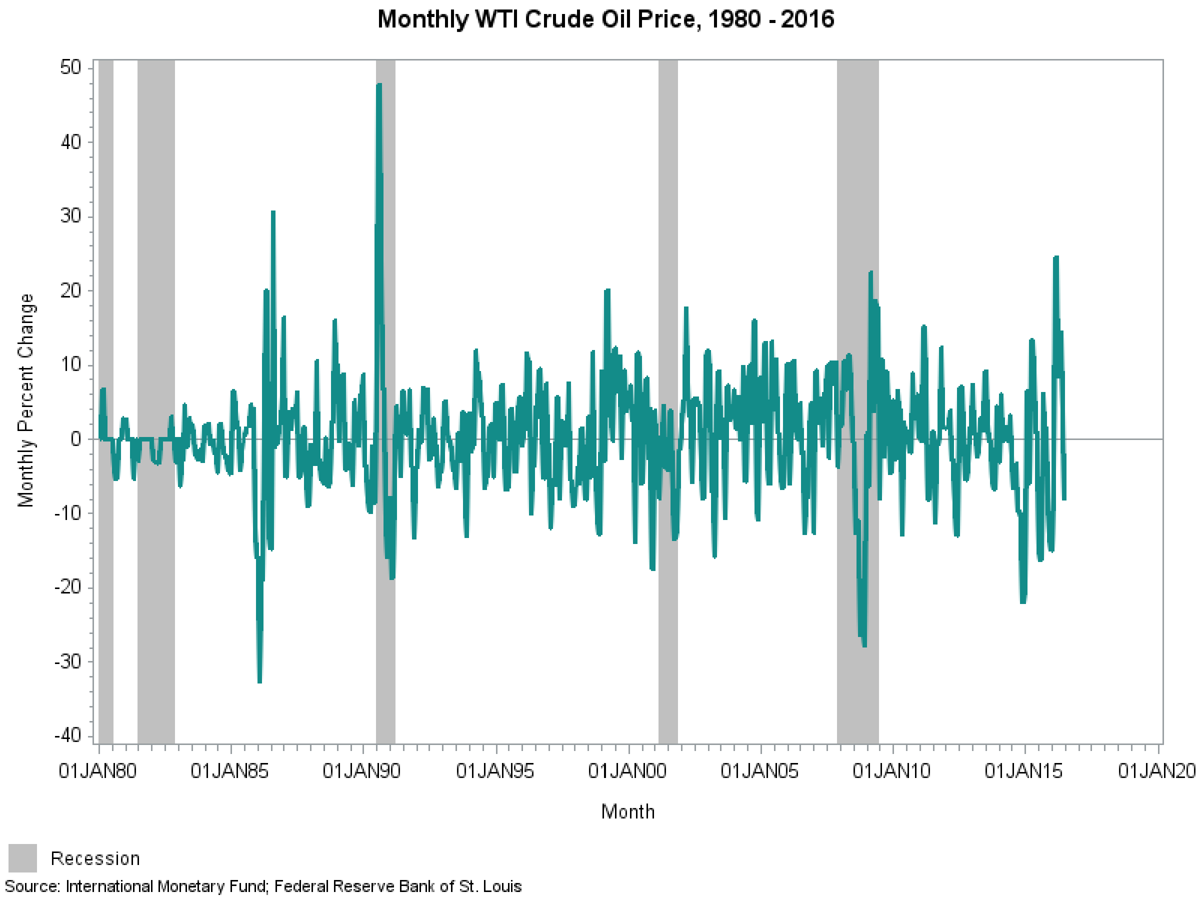


Figure 7: Monthly Change in Global Crude Oil Prices, 1980 - 2016

Period t-1	Period t	Period t+4
Exploration Decision **(Exploration Costs incurred)** **(Price of Oil in Period t+4 estimated)**	**Reserves Added**	**Reserves Extracted** **(Extraction Costs incurred)**

Figure 8: Hydrocarbon Exploration Across Periods

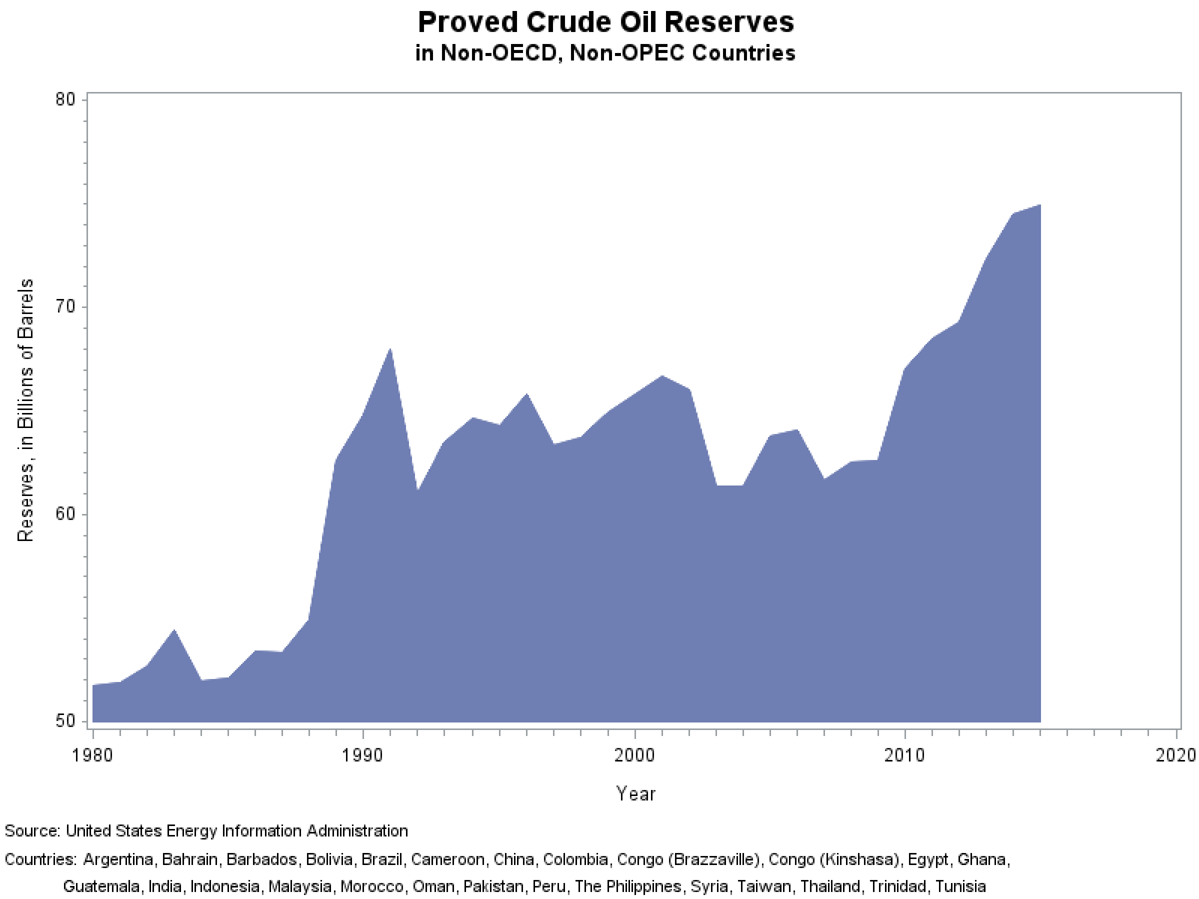


Figure 9: Estimated Proved Crude Oil Reserves of Sample, 1980 - 2015

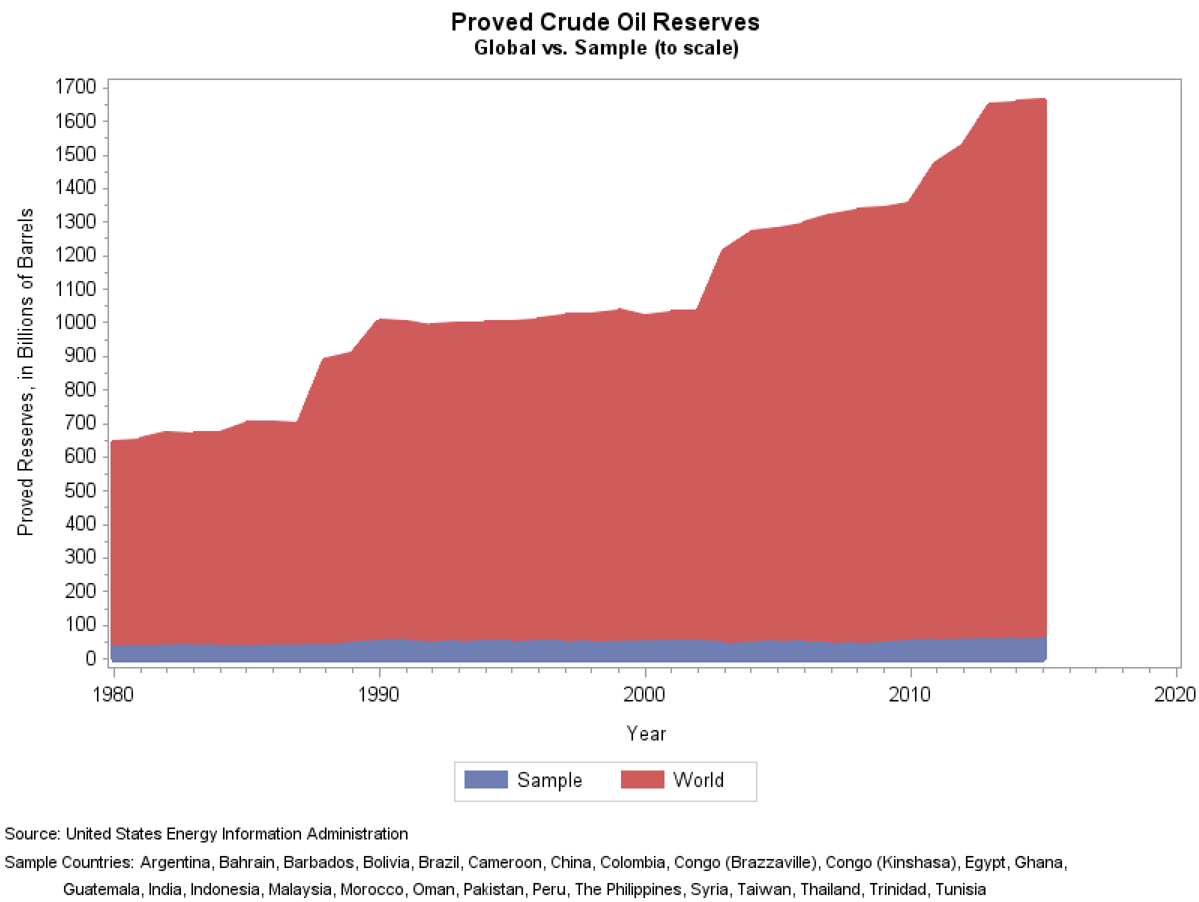


Figure 10: Estimated Global and Sample Proved Crude Oil Reserves, 1980 - 2015

Table 1: Sample of Non-OECD, Non-OPEC Countries

Country	Reserves (Billions of Barrels, 2015)	Land and Water Area (km^2, 2016)	Population (2016)
Argentina	2.3542	2,780,400 (8^{th})	43,886,748 (33^{rd})
Bahrain	0.12456	760 (188^{th})	1,378,904 (156^{th})
Barbados	0.00253	430 (202^{nd})	291,495 (181^{st})
Bolivia	0.2098	1,098,581 (28^{th})	10,969,649 (82^{nd})
Brazil	15.3142	8,515,770 (5^{th})	205,823,665 (6^{th})
Cameroon	0.2	475,440 (54^{th})	24,360,803 (53^{rd})
China	24.64884	9,596,960 (4^{th})	1,373,541,278 (1^{st})
Colombia	2.445	1,138,910 (26^{th})	47,220,856 (30^{th})
Congo, Brazzaville	1.6	342,000 (64^{th})	4,852,412 (125^{th})
Congo, Kinshasa	0.18	2,344,858 (11^{th})	81,331,050 (18^{th})
Egypt	4.4	1,001,450 (30^{th})	94,666,993 (16^{th})
Guatemala	0.08307	108,889 (107^{th})	15,189,958 (71^{st})
India	5.67479	3,287,263 (7^{th})	1,266,883,598 (2^{nd})
Indonesia	3.6925	1,904,569 (15^{th})	258,316,051 (5^{th})
Malaysia	4	329,847 (67^{th})	30,949,962 (42^{nd})
Morocco	0.00068	446,550 (58^{th})	33,655,786 (40^{th})
Oman	5.151	309,500 (71^{st})	3,355,262 (134^{th})
Pakistan	0.371	796,095 (36^{th})	201,995,540 (7^{th})
Peru	0.74122	1,285,216 (20^{th})	30,741,062 (44^{th})
Philippines	0.1385	300,000 (73^{rd})	102,624,209 (13^{th})
Syria	2.5	185,180 (89^{th})	17,185,170 (66^{th})
Taiwan	0.00238	35,980 (139^{th})	23,464,787 (55^{th})
Trinidad	0.7283	5,128 (174^{th})	1,220,479 (160^{th})
Tunisia	0.425	163,610 (93^{rd})	11,134,588 (80^{th})

Country information was gathered from the CIA World Factbook.

Table 2: Sample Descriptive Statistics
1980 - 2015

	Reserves	Δ Reserves	Oil Prices	Δ Oil Prices
Units	Billions of Barrels	Percent Change	US Dollars	Percent Change
Std. Dev.	4.58	0.59	27.77	0.24
Variance	21.01	0.35	770.95	0.06
Mean	2.61	0.07	41.25	0.04
Minimum	0.00	-0.90	14.42	-0.48
Maximum	24.65	9.42	99.67	0.57
N	840			

Table 3: Estimation Results for Baseline Model

Dependent Variable: Percent Change in Proved Oil Reserves, $\Delta ln(R_{it})$

Variable	OLS FE	OLS RE	Pooled OLS	2SLS FE
$Intercept$	-3.437	2.267	2.882	1.601
	(3.562)	(2.077)	(2.198)	(24.964)
$ln(P^e_{t+4})$	-0.062	-0.017	-0.012	0.038
	(0.046)	(0.027)	(0.027)	(0.494)
$ln(R_{it-2})$	-0.155***	-0.021***	-0.008**	-0.148***
	(0.025)	(0.007)	(0.004)	(0.035)
$NAT_{it} = 1$	-0.079**	-0.010	-0.013	-0.105
	(0.034)	(0.032)	(0.015)	(0.134)
$NAT_{it} = 2$	-0.147**	-0.043	-0.033*	-0.171
	(0.060)	(0.034)	(0.018)	(0.135)
$trend$	0.002	-0.001	-0.001	-0.001
	(0.002)	(0.001)	(0.001)	(0.013)
Model DF	787	810	810	787
In-Sample Goodness-of-Fit (R^2)	0.0931	0.016	0.0102	0.091
Joint Significance of Fixed Effects (F-Stat)	3.13 ($p < 0.0001$)			2.31 ($p < 0.0001$)
Cross Sections	24			
Time Periods	34			
Observations	816			

Standard Deviations are in parentheses. * denotes statistical significance at the 90% level, ** 95% and *** 99%. OLS with fixed effects estimation has fewer DFs than random effects and pooled OLS due to the fixed effects. 23 indicator variables are used in the model to measure the fixed effects of the 24 countries in the sample: $DF = N - (\#of covariates + 1) - (\#of indicator variables) = 816 - 6 - 23 = 787$. Under random effects and pooled OLS estimation, $DF = N - (\#of covariates + 1) = 816 - 6 = 810$

Table 4: Estimation Results for Alternative Models 8.1, 8.2, 8.3

Dependent Variable: Percent Change in Proved Oil Reserves, $\Delta ln(R_{it})$

Variable	(1)	(2)	(3)	(4)
$Intercept$	-3.449	-3.461	-3.137	-3.537
	(3.580)	(3.343)	(3.577)	(3.517)
$ln(P_{t-1})$	0.024			
	(0.032)			
$ln(P_{t-2})$	-0.097*			
	(0.052)			
$ln(P_{t-3})$	0.071			
	(0.044)			
$ln(P_{t-4})$	-0.038			
	(0.026)			
$ln(\bar{P}_{lag})$		-0.039		
		(0.024)		
$ln(P^{e}_{t+4})$			-0.070	-0.051
			(0.047)	(0.050)
$ln(R_{it-2})$	-0.157***	-0.156***	-0.157***	-0.154***
	(0.026)	(0.026)	(0.026)	(0.025)
$\Delta ln(P_{t-1})$			0.060**	
			(0.030)	
$\sigma^2_{P_t}$				-0.0001
				(0.0001)
$NAT_{it} = 1$	-0.072**	-0.075**	-0.072**	-0.080**
	(0.034)	(0.034)	(0.033)	(0.032)
$NAT_{it} = 2$	-0.141**	-0.144**	-0.141**	-0.149**
	(0.060)	(0.060)	(0.060)	(0.059)
$trend$	0.002	0.002	0.002	0.002
	(0.002)	(0.002)	(0.002)	(0.002)
Model DF	784	787	786	786
In-Sample Goodness-of-Fit (R^2)	0.0975	0.0937	0.0939	
Joint Significance (F-Statistic)	3.17 ($p < 0.0001$)	3.16 ($p < 0.0001$)	3.18 ($p < 0.0001$)	3.09 ($p < 0.0001$)
Cross Sections	24			
Time Periods	34			
Observations	816			

Table 5: Estimation Results for Alternative Models 8.4 and 8.5

Dependent Variable: Percent Change in Proved Oil Reserves, $\Delta ln(R_{it})$

Variable	(5)	(6)
$Intercept$	-4.233	-4.283
	(3.451)	(3.431)
$ln(P^e_{t+4})$	-0.071	-0.050
	(0.044)	(0.058)
$ln(R_{it-2})$	-0.156***	-0.155***
	(0.025)	(0.025)
IOC_{it}	0.069	0.163
	(0.051)	(0.186)
$IOC_{it} * ln(P^e_{t+4})$		-0.026
		(0.047)
$trend$	0.002	0.002
	(0.002)	(0.002)
Model DF	788	787
In-Sample Goodness-of-Fit (R^2)	0.0917	0.0918
Joint Significance (F-Statistic)	3.08 ($p < 0.0001$)	3.08 ($p < 0.0001$)
Cross Sections	24	
Time Periods	34	
Observations	816	

Table 6: Estimation Results for Alternative Model 8.7

Dependent Variable: Percent Change in Area-scaled Proved Oil Reserves, $\Delta ln(\widetilde{R}_{it})$

Variable	(6)
$Intercept$	-5.294
	(3.743)
$ln(P^e_{t+4})$	-0.062
	(0.046)
$ln(\widetilde{R}_{it-2})$	-0.155***
	(0.025)
$NAT_{it} = 1$	-0.079**
	(0.034)
$NAT_{it} = 2$	-0.147**
	(0.060)
$trend$	0.002
	(0.002)
Model DF	782
In-Sample Goodness-of-Fit (R^2)	0.0931
Joint Significance (F-Statistic)	3.02 ($p < 0.0001$)
Cross Sections	24
Time Periods	34
Observations	816

Table 7: Estimation Results for Alternative Models 8.8 and 8.9

Dependent Variable: Percent Change in Proved Oil Reserves, $\Delta ln(R_{it})$

Variable	(7)	(8)
$Intercept$	-10.9291	-10.2394
	(7.4811)	(7.6925)
$ln(P^e_{t+4})$	-0.1069	-0.1089
	(0.0785)	(0.0783)
$ln(R_{it-2})$	-0.1563***	-0.1603**
	(0.0224)	(0.0223)
$NAT_{it} = 1$	-0.0687**	-0.0805**
	(0.0346)	(0.0349)
$NAT_{it} = 2$	-0.0828*	-0.1089**
	(0.0433)	(0.0490)
pol_{it}	-0.0003	
	(0.0006)	
gov_{it}		-0.0023
		(0.0018)
$trend$	0.0056	0.0054
	(0.0039)	(0.0040)
Model DF	450	450
In-Sample Goodness-of-Fit (R^2)	0.1162	0.1208
Joint Significance (F-Statistic)	2.41 ($p = 0.0003$)	2.54 ($p < 0.0001$)
Cross Sections	24	
Time Periods	20	
Observations	480	

Table 8: Stepwise Estimation Results for Baseline Model

Dependent Variable: Percent Change in Proved Oil Reserves, $\Delta ln(R_{it})$

Variable			
$Intercept$	0.086	-0.010	0.123
	(0.078)	(0.074)	(0.079)
$ln(P^e_{t+4})$	-0.022	-0.021	-0.044**
	(0.021)	(0.021)	(0.021)
$ln(R_{it-2})$	-0.149***	-0.145***	
	(0.022)	(0.023)	
$NAT_{it} = 1$	-0.094***		
	(0.030)		
$NAT_{it} = 2$	-0.165***		
	(0.060)		
Model DF	788	790	791
In-Sample Goodness-of-Fit (R^2)	0.0916	0.0876	0.0125
Joint Significance (F-Statistic)	3.11 ($p < 0.0001$)	3.01 ($p < 0.0001$)	0.34 ($p = 0.9984$)
Cross Sections	24		
Time Periods	34		
Observations	816		

Table 9: AR(1) Estimation Results for Annual Crude Oil Prices

	1947 - 2015 (Available data)	1975 - 2015 (Used for P^e_{t+4})
$Intercept$	2.04924	4.92134
	(1.48505)	(3.15982)
P_{t-1}	0.94117***	0.89236***
	(0.04179)	(0.06863)
In-Sample Goodness-of-Fit (R^2)	0.8833	0.8125
Observations	69	41