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Memorandum

Date: April 6, 2009

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Re: Draft Proposed OCS Oil and Gas Leasing Program 2010-2015

Summary

The Draft Proposed Program ("DPP") prepared by the Minerals Management Service ("MMS") and the methodology that underlies the economic valuation of leases fails to take into consideration the *irreversibility* of extraction decisions and price uncertainty for nonrenewable resources such as oil and natural gas. This failure systematically overstates the value of immediate resource extraction, and seriously biases the DPP in favor of expanded leasing. **Decisions based on this flawed methodology could cost the American public hundreds of billions of dollars.**

This methodological flaw is based on the use of a simple net present valuation ("NPV") technique for the leasing decision, which fails to take account of irreversibility and uncertainty. Economic literature on the subject of irreversible decisions has acknowledged for decades that theses decisions cannot be rationally characterized through a simple NPV maximization formula. As Dixit and Pindyck stated in an early textbook on the subject: "[T]he simple NPV rule is not just wrong; it is often *very* wrong."[1] In the case of the DPP, it means that the true value of the option to wait to extract is entirely ignored, which leads to economically unjustified results.

The following comments explain how the DPP relies on a NPV calculation, and discusses why irreversibility cannot be adequately modeled using an NPV formula. It then explains how a "real options" model better characterizes the decision faced by the MMS, and shows how the NPV formula creates a unidirectional bias in favor of early exploitation, resulting in the inefficient extinguishing of option value. The loss of this option value is estimated using a rough calculation based on the assumptions given by MMS about resource extraction costs and prices. The comments close with recommendations for reform.

Use of the Net Present Value Model in the DPP

Under Section 18(a)(1) of the Outer Continental Shelf Lands Act (OCSLA), the Secretary of the Interior is directed to prepare an "oil and gas leasing program . . . indicating, as precisely as possible, the size, timing, and location of leasing activity which he determines will best meet national energy needs for the five-year period following its approval."[2] The leasing program and management of the outer continental shelf ("OCS") must be "conducted in a manner which considers *economic*, social, and environmental values of the renewable and *nonrenewable resources* contained in the outer Continental Shelf."[3]

The primary means through which the DPP fulfills the statutory mandate to consider economic costs is through the estimation of a "Net Social Value" (NSV) that "provides the Secretary with estimates of net economic value and environmental/social costs associated with the ultimate recover of all economically recoverable oil and natural gas resources" within particular OCS zones.[4] This NSV can be disaggregated into two parts: "Net Economic Value" (NEV) and "environmental and social costs."[5]

The DPP cites to the paper *Economic Analysis for the OCS 5-Year Program 2007-2012: Theory and Methodology* (MMS 2007-017) ("MMS *Economic* Analysis") for "[a] more detailed explanation of the methodology employed by MMS for its net economic and social benefits analysis."[6] MMS *Economic Analysis* states that "CBA [cost-benefit analysis] has sanctioned a specific measure for determining the desirability of a public action. This measure is the present value of the future stream of net social benefits (gross benefits minus gross costs) from the investment or policy."[7] MMS *Economic Analysis* also states that "the development of estimates using [the CBA] approach and the Secretary's consideration of those estimates is consistent with a legally sanctioned foundation for decisions concerning OCS leasing."[8]

In MMS *Economic Analysis*, the "total benefits consist of the economic rent (producer surplus) plus the consumer surplus," where "[e]conomic rent is the difference between the total revenue collected by producers and their total costs of production," and "[c]onsumer surplus is the difference between the maximum that consumers would be willing to pay . . . and what they actually had to pay at the market clearing price."[9] Oil production is also assumed to "impose[] external environmental costs on society," including "air pollution, risk of oil spills, [and] pressure on overtaxed local services."[10]

NEV is defined as anticipated production multiplied by price, minus development costs, summed over time and discounted to the present value using a seven percent discount rate.[11] Environmental costs are computed as the sum of environmental externalities, discounted at the same rate.[12] The NSV is the difference between NEV and environmental costs. MSS *Economic Analysis* accounts for consumer surplus by adding that to NSV to compute the "net benefits" of production.[13] In the DPP, consumer surplus is not taken into account[14]

On the basis of this technique, MMS summarizes the NSV of immediate drilling in each of the regions under review, finding NSV estimates that range between zero and hundreds of billions of dollars in certain regions. The total benefit projected by the projects is estimated between hundreds of billions and trillions of dollars.[15]

With respect to timing, the DPP "assume[s] all of a planning area's unleased resources are leased simultaneously,"[16] and MMS then conducts sensitivity analysis "in which the results are calculated using two [alternative] sets of timing assumptions"[17]—the simultaneous assumption, and an assumption that "all resources [are] leased, discovered, developed, and produced in the first year of the program."[18] The results from the stronger "first year" assumption are compared with the standard analysis to determine sensitivity to this assumption.

The DPP acknowledges the reality of price instability in the market for oil and natural gas:

> The experiences of the last few decades have shown that unanticipated events or economic changes can cause oil and gas price paths to deviate considerably from even the most respected forecasts, so MMS uses the level-price-scenario approach to allow decision makers to more easily envision the effects on NEV of major swings in price, either upward or downward. During the 18 months preceding the completion of this analysis, oil prices rose and fell by approximately $80 per barrel, indicating a need to present decision makers with a wide range of price possibilities. In addition, because the recent precipitous price decline was due largely to a serious economic crisis that suddenly constrained demand, prices could easily begin another steady rise as global economies (and thus demand) recover during the new 5-year lease sale schedule. The changing balance between supply and demand would be exacerbated by decisions to curtail or delay high-cost investments (to increase supply) that were planned as prices reached and surpassed historic highs.[19]

The DPP accounts for price instability as follows:

> [T]he current analysis includes low and high price scenarios with a $100-per-barrel range as well as a mid-point price scenario that is considerably higher than market prices at the time of the analysis. Estimates of NSV are considered for . . . three level, inflation-adjusted price scenarios.[20]

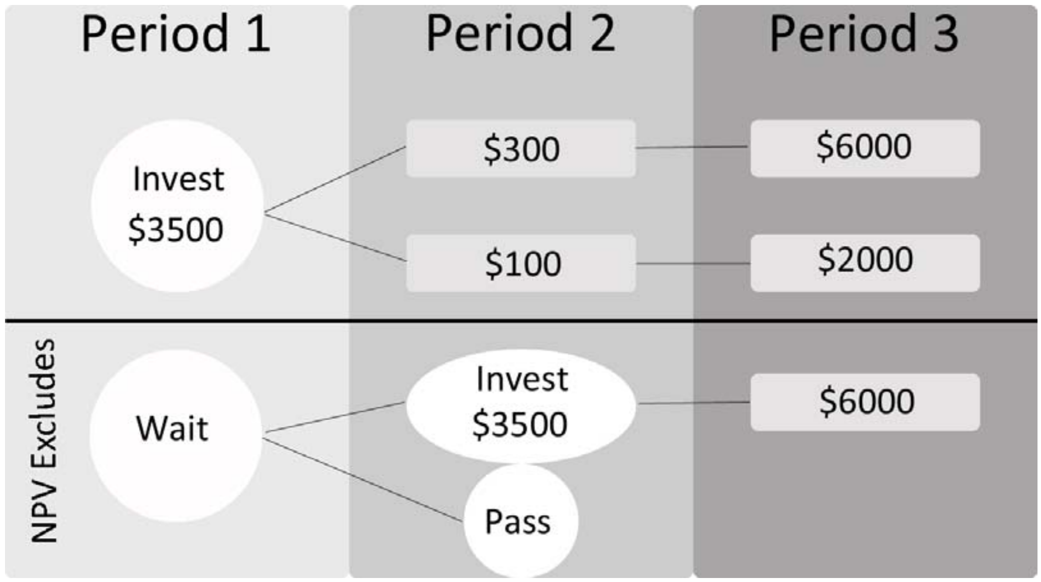
The Problem of Irreversibility and Uncertainty

The NPV model employed by MMS has a very important flaw: It fails to take into account the option value of drilling. The United States does not face a one-off decision of whether to lease drilling rights or not. Rather, it faces an on-going, irreversible decision whether to lease drilling rights or not. These types of irreversible decisions are not well conceptualized under the NPV model, because it fails to account for the informational value of waiting. The best analogy to the leasing decision is not a single and binding decision, but rather an *option* to lease drilling rights, available now or any time in the future. The decision is whether to *exercise* that option.

A net present value framework is sufficient when a decision-maker is faced with a single one-off choice whether a project should be pursued or not. However, as owners of an option to lease drilling rights, the United States is not faced with such a simple question. The question is whether to lease drilling rights *now*. And the simple net present value calculation employed by MMS cannot answer that question because it fails to take into account uncertainty about future price of oil. Oil prices are volatile and are subject to large degrees of variability. The net present value framework assumes away that uncertainty, and is therefore impoverished as a mechanism to determine the timing of decisions.

A simple numerical example can illustrate how the NPV framework can lead to incorrect answers in the case of irreversibility and uncertainty.

Figure 1. Simple Example of Flaw in NPV Framework



There are three periods. The investor can invest in period one or two. The investor does not know future payoffs in period one, and only knows that there is equal chances of either: A) a $300 payoff in period two and $6000 payoff in period three; or B) a $100 payoff in period two and $2000 payoff in period three. In period two, the payoffs for that period and period three are disclosed. To receive the payoff, the investment must be made in the prior period. In this simple model, there is not discount rate because it is irrelevant for outcomes.

Using the NPV framework in period 1, the investor would make the investment because the value of the payoffs is .5($300+$6000)+.5($100+$2000)=$4200, which is greater than the $3500 investment. The net expected benefit is $700.

However, using a simple option calculation, we can see that there is value to waiting until period 2 to decide whether to invest. The choice to wait has a payoff of .5($6000)=$3000 minus an expected investment cost of .5($3500)=$1750 for a total net expected benefit of $1250.

A simple NPV calculation fails to account for the potential value of waiting, and can therefore give very incorrect results. Here, the rational investor would wait until period two to make an investment decision.

The NPV model cannot tell MMS whether it is wise to lease drilling rights today, tomorrow, or twenty years from now. To answer that question, MMS must first take into account uncertainty about the price of oil. To do this, MMS must treat natural resource extraction as an option and, from that foundation, build a framework that can guide it in timing extraction decisions.

Three Embedded Options

For twenty years, economists have modeled a variety of investment decisions in areas as diverse as resource extraction and real estate management as "real options." The concept was popularized by a set of scholars writing from the late 1980s through the late 1990s.[21] Financial mathematicians and economists have developed a variety of models to deal with the specific situations presented by diverse real options contexts: alternative energy investment,[22] remediation of brownfield properties,[23] and the development of real estate.[24] A sub-literature has sprung up on real options in the natural resource extraction context, with a special focus on the development of petroleum reserves.[25] Books for specialists and practitioners have been developed,[26] and there is even an international real options society that holds regular conferences.[27]

Applying this literature to the question of federal leasing of drilling rights, the United States government is the ultimate owner of all mineral rights under federal lands, including the sea bed. The government enjoys the right to develop, or not develop those minerals itself, or to sell its rights. It can therefore be thought of as a traditional owner of mineral rights, constantly facing three choices on the margin: to explore, to develop, and to extract. There are further theoretical options—the holder of mineral rights could suspend production or abandon the well after production began but before production is over. Because of high costs associated with these theoretical options, they are seldom exercised, and can be ignored for the time being.

The three options—exploration, development, and extraction—are interrelated, and the value of each is ultimately dependant on the market price of oil and gas. At the end of each stage, the holder of the option has the ability to exercise or postpone, based on the current information. As time passes, the holder of the option receives more information on prices, and can make a more informed choice about whether to exercise the option or not.

Prior to the first stage of development, there are enormous levels of uncertainty about any petroleum reserve. Not only are future prices unknown, but the amount of the resources that are owned and accessible is unknown as well. Exploration is designed to reduce some of those uncertainties and estimate the value of moving forward with the project. Various seismic and drilling tests are conducted to determine the amount of oil and gas that is available for extraction and estimate a sunk and per unit cost to take the minerals out of the ground. Exploration allows the owner of the right to have a more accurate picture about the total amount of oil and gas and the costs of production before deciding whether to proceed with development.

If exploration has returned sufficiently favorable results to move forward, then development can begin. During the development stage, the infrastructure for extracting and transporting the oil and gas are put in place. Pipelines and deep-sea oil platforms are constructed, land is cleared, and drilling works are put together. Once the development phase is complete, oil and gas can be extracted at will. However, because production has not actually begun, the option to wait remains. Once production starts, the available options (other than continuing production) are to suspend production or abandon the well, both of which come with very high costs.

Finally, at the production state, resources are extracted from the ground and sold on the market. The production stage can last for many years, depending on the size of the reserve. The speed of production will depend on the equipment that was initially installed, the rate of maintenance, and any upgrades that are put in place. Once production is complete, "shut-down" and compliance with all environmental regulations for closing the well and removing equipment occurs.

While the government could theoretically pursue exploration, development, and production on its own, it has generally turned to private markets. In the current structure of oil leases, the American government sells lease holders the option to explore, develop, and produce from fixed tracts of land (including the seabed), subject to relevant regulations and an expiration date. After the lease expires, the leaseholder relinquishes all rights to the property, unless a commercially viable amount of oil or gas is being extracted.

The current structure of the lease arrangement encourages the leaseholder to immediately explore and develop (if practicable). Because leases are finite in duration, the holder does not have the option to wait forever—there is a very fixed timeline during which exploration and development must take place, and production must start. Leaseholders are free to simply wait out the term, so there is no *obligation* to move forward with the project. But, because of the finite nature of mineral leases, they can only wait for so long before making an ultimate decision about what to do—either move forward or relinquish the right forever.

The government lays off much of the risk of oil extraction onto the private sector, but it pays a cost for transferring the risk. Obviously, a risk premium is built into the price of leases, reflecting the fact that a lease may not ultimately return any profit. That premium should be similar to the risk premium common in other financial markets.

Perhaps more importantly, the government does not transfer a perpetual right, and it therefore retains absolute control of the timing of resource extraction. If a perpetual right were transferred, private leaseholders would determine the optimal time to exercise their various options. However, that is not how the law works, and there are technical challenges to creating such a regime.[28] The government then has the task of determining the optimal timing of drilling, because once leases are released, they are likely to be used if commercially viable.

The government could structure its policy to maximize the information that it has at each step of the process. For example, as leases are released into the market and exploration and development begins, information is created about the extent of oil reserves in certain areas. This information can be used as the basis for future lease sale decisions. In an extensive study of the implications of tax policy for extraction, Professor Strnad looks at tax tools that can lead to a variety of incentives for private development that have implications for how government can exercise its option to sell leases.[29] Perhaps most straightforwardly, the government can simply commission a study of energy resources, if the added value of the information is ultimately worth the initial investment.

The choices facing government are therefore complex. Under the current law, however, the focus is on a fairly straightforward "drill or don't drill" dynamic. A full accounting of the government's options would look to the variety of policy choices available, including the financing of exploration activities and the structuring of tax policy to encourage immediate exploration but delayed development. The geological conditions could also be examined to see if they could allow the government to auction perpetual leases, thereby allocating the market the decision of when to drill.

The DPP should expand its range of policy analysis to include the greater number of alternatives illuminated by the options framework. **At an absolute minimum, MMS must expand its analysis to include the option value of waiting to lease.**

Basic Option Valuation

In an option arrangement, there is a party and counter-party. A call option gives the holder the right to purchase some instrument (often the stock of a corporation) at some price.[30] That price is called the exercise price or the "strike" price. When a call option is exercised, the value of the option is the difference in the price of the underlying instrument and the strike price. Thus, an option to purchase fifty IBM shares at $30 a share is worth $500 if that option is exercised when IBM shares are trading at $40: ($40 – $30) * 50 = $500.

The simplest way to value an option is to look at the difference between the strike price and the market price. With this formula, any "in the money" option—i.e. where strike price is lower than the market price—is valued at the difference between the market and strike prices. Options for which the market price is lower than the strike price—"out of the money options"—would be valued at zero.

We know that this model is too simplistic, because "out of the money options" are not valued at zero. As a factual matter, they trade at non-zero prices on financial markets. This is not irrational because there is some probability that the price of the underlying instrument will go above the strike price and deliver value to the holder of the call option. Because that probably is not zero, "out of the money" options have value, even if they can not be cashed in immediately. Only at its time of expiration, when the probability of a price increase putting the option "in the money" diminishes to zero, is the value of an "out of the money" option extinguished.

Financial economists struggled for some time to develop a model that would capture the value conferred by options. In 1973, economist Robert C. Merton developed the first successful mechanism to value European options. For a European call option, the holder has the right to purchase the stock at the time the option expires, but not before. The valuation formula for a European call option, known as the Black-Scholes formula, is lengthy,[31] but there are five variables in play: (1) price where the stock is currently trading; (2) strike price of the option; (3) expiration in years of the option; (4) risk-free rate of return; and (5) volatility of the underlying asset. Taken together, these variables define the probability distribution for all "in the money" outcomes at expiration. The weighted sum of these probabilities is the value of the option.

With a basic understanding of options, it is not hard to see how natural resource extraction can be understood as an option. First, we know the price where the underlying asset—the natural resource in question—is currently trading. The analogy to the strike price in the natural resource context is the cost of extracting the resource. It is the price that must be paid to own the underlying asset. The risk-free rate of return is given—usually estimated as the return on a 30-year U.S. Treasury Bill. Estimating future volatility in oil prices—as with any asset—is the trickiest part of option valuation, but past prices provide a rough guide.

For a European call option, there is a fixed expiration period that does not exist for drilling options, a problem addressed below. However, it is worth noting that, if policymakers were faced with the choice of drilling today, or waiting for a fixed period of time and then making a final decision to drill, they would maximize value by waiting—taking into account purely the value of the oil minus the cost of extraction.

The following chart gives a flavor of how time affects the value of an option, using assumptions from a recent NPV calculation of increasing access to offshore drilling[32] on the price of oil ($100) and cost of extraction ($20), a risk-free rate of return of 3%, and assuming volatility in oil prices of 30%.

Table 1 European Options to Drill

Expiration Period	Option Value (per barrel)
1 day	$ 80.00
1 month	$ 80.05
6 months	$ 80.30
9 months	$ 80.44
1 year	$ 80.59
2 years	$ 81.16
5 years	$ 82.82
10 years	$ 85.46
20 years	$ 89.81
30 years	$ 92.88

Based on the European option analysis, waiting to lease the oil drilling rights would be favored. The current value of oil, minus the cost of extraction, is $80. The value today of an option to drill in thirty years is $92.88. Exercising the option now would destroy that additional value of $12.88.

Real Option Valuation

The European call option formula is inadequate because MMS does not face a single choice to either lease drilling rights now or in thirty years. MMS has flexibility to drill at any time, and therefore holds an "American-style" option in which the option also has no expiration date and is therefore perpetual.[33]

The valuation of perpetual options is a tricky and complex exercise, but financial economists have developed models to assign values to these options and—as importantly—to assign conditions to when exercise of these options is rational. The European call option formula cannot be imported into the perpetual context because it is always rational for the holder of such an option to wait until expiration to cash in the option, no matter how high the current trading price of the underlying asset. So long as there is equal chance the price of the asset will increase in price as decrease in price, then the holder should wait to exercise the option. However, in the perpetual context, this leads to an incoherent result—because there is no expiration, it is never rational to cash in the option, rendering the option worthless.

Dixit and Pindyck provide a fairly straightforward formula to derive a "threshold price" (the "DP threshold price") at which it is rational to cash in a perpetual option.[34] This price represents the point at which the potential for lost returns from not holding the asset is greater than the risk of loss from potential future falls in the price of the asset.

The basic underpinnings of the DP threshold price are the "convenience yield" and an assumption of Brownian motion of asset prices. The "convenience yield" is the extra value of holding an asset rather than an option on that asset. In the context of common stock, it is the dividend of the stock: The holder of the asset receives the dividend, but not the holder of an option. The dividends during the time prior to exercise of an option are losses for the option holder.

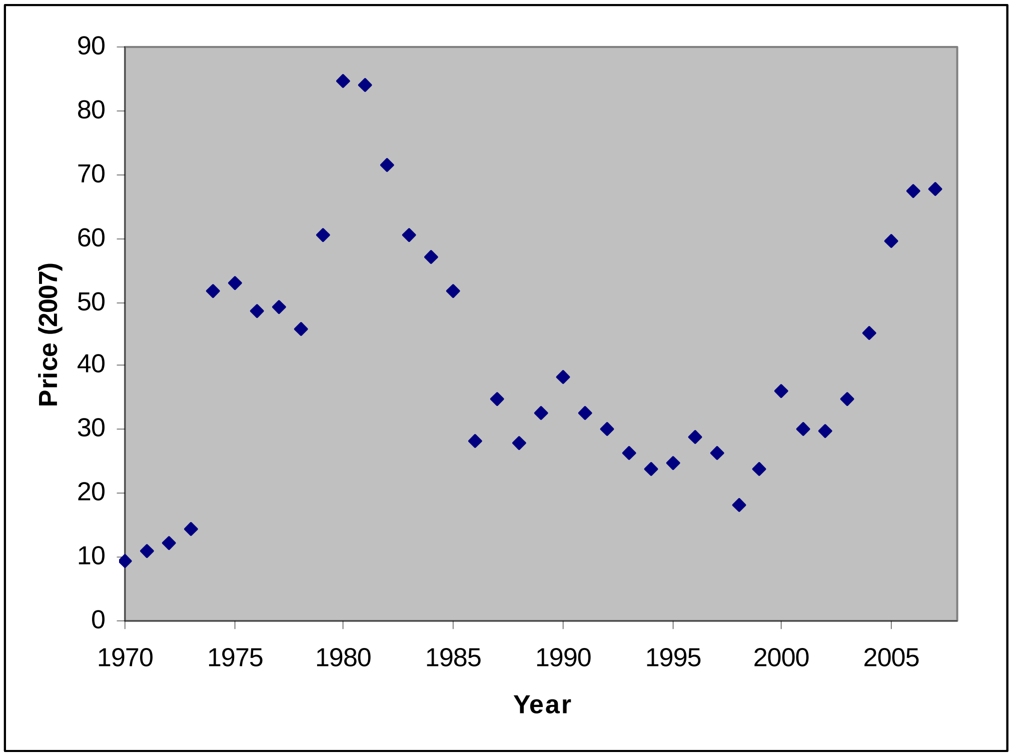
The second underpinning of the DP threshold price is the assumption of Brownian motion. Under this assumption, the future prices of an asset are random and determined by a probabilistic process based on a normal (Gaussian) distribution—i.e. the bell curve. A term in models of Brownian motion allows for "drift" so that over time, the motion will tend in one direction or the other. For asset prices, that amounts to an assumption of an upward drift in asset prices over time, usually tied to the risk-free rate of return.[35]

The threshold price equates the lost option value with the lost convenience yield. Once an asset price reaches a certain level, the risk from the probability that the price will fall below the strike price is sufficiently low that it is no longer worthwhile to forgo the convenience yield. To derive the threshold price, the input variables are the current price, the strike price, the risk-free rate of return, the convenience yield, and price volatility.

Wealth Losses from Failure to Account for Options Value

Using the DP formula and inputting the numerical estimates concerning production costs and average oil prices (and putting aside external factors for the sake of simplicity), a threshold price for oil can be derived that would dictate when it is time to cash in. The risk-free rate of return is traditionally set to equal the return on United States Treasury Bills, with 3% chosen as a fairly standard measure over time. To derive a rough estimate of oil volatility, we can look at the standard deviation of yearly oil prices since 1970:

Figure 2: Yearly Oil Prices,1970-2007[36]



Based on this data, the standard deviation on yearly oil prices from 1970 through 2007 is $20. The average price during that same period was $40.35. The relative standard deviation is 49%. Because it is based on yearly data and misses the wild recent volatility, that is a conservative estimate of price volatility.

The convenience yield is somewhat difficult to derive in the oil context. The convenience yield is defined as the added benefit that accrues when one holds an asset rather than a derivative instrument on that asset. The necessity of adjusting for a convenience yield is best illustrated in the context of dividend-paying stocks. The person holding the stock receives the dividends until the option holder exercise the option—a benefit to the stock holder and a cost to the option holder.

The term "convenience yield" has a more specific understanding in the oil context, and has to do with the expected relationship between spot prices and forward prices on oil. Theoretically, the forward price on a barrel of oil should equal the expected spot price on the delivery date adjusted for the discount rate and the price of storage. As an empirical matter, that relationship does not hold—there are times when the forward market is in "backwardation," where the spot price exceeds the adjusted forward price. Assuming that the market is in equilibrium, the explanation for backwardation is that there is some convenience yield to holding oil rather than a forward contract on that oil. One explanation for this convenience yield for oil is that it "arises from the flexibility that stocks provide firms to produce when costs are low, or to avoid costly changes in production."[37] Reasonable estimates of the convenience yield on oil have ranged between 2.5% and 8%.[38]

The threshold price is sensitive to this input as well. The difference between the threshold prices with assumptions of 2.5% or 8% vary by a factor of 2.5.

The DPP does not publish its estimates of the production costs in the various areas under consideration. A recent cost-benefit analysis proposes a rough cost of $20 per barrel, although this is likely an underestimate for many offshore areas.[39] With a convenience yield of 5.25% (the midpoint) the threshold price of oil is roughly $76. If the convenience yield is on the low end of the above range, the threshold price is closer to $140, and if the convenience yield is on the high end, the threshold price is closer to $60. The threshold price is also very sensitive to changes in estimates of the marginal cost of production, with the threshold price amplifying by as much as four times any errors in estimating production costs.

Using the midpoint convenience yield, the lost option value at the low price estimate of $60 per barrel used in the DPP would be $16 per barrel. **Based on MMS estimates of available resources, the lost option value could therefore exceed $626 billion.**

Necessary DPP Revisions

The DPP states that:

> While it is relatively easy to remove lease sales from the 5-year schedule if prices and industry interest fall, this is not true if soaring prices indicate a need for a more aggressive schedule. The Secretary does not have legal authority to add lease sales to a 5-year schedule once it is in place, regardless of changing conditions.[40]

While this may be true, it does not justify blindness within the DPP to the irreversibility of the leasing decision given price uncertainty. Instead, the DPP should, while giving the Secretary flexibility, include strict decisionmaking criteria that will describe the conditions under which the Secretary should open an area for leasing.

MMS should make the following revisions:

- The DPP should explicitly embrace an options framework, rather than an NPV model, for estimating the economic consequences of lease drilling rights;

- Building on the DP threshold price model, and making appropriate revisions to account for risk-aversion and non-tradability of assets, the DPP should develop a specific model for pricing the option value of the choice to wait to lease drilling rights;

- Relying on existing literature and its own analysis, the DPP should include an estimation of the convenience yield for oil and natural gas, as well as an appropriate estimated price volatility for those commodities;

- The DPP must be more explicit in how it estimates production costs and future prices, because the potential net social benefit of immediate leasing—and whether such leasing is economically justified—will be closely contingent on those estimates;

- On the basis of its option valuation model and its estimates of production costs, future prices, risk-free return, convenience yield, and price volatility, the DPP should include threshold prices for resources for all areas under consideration, and leases should not be auctioned unless prices are above the threshold for a specified period of time.

Notes

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[1] AVINASH K. DIXIT & ROBERT S. PINDYCK, INVESTMENT UNDER UNCERTAINTY 136 (1994).

[2] Outer Continental Shelf Lands Act Amendments of 1978, Pub. L. No. 95-372, § 208, 92 Stat. 629, 649-52 (adding § 18 to OCSLA) (codified at 43 U.S.C. § 1344) [hereinafter OCSLA § 18].

[3] OCSLA § 18(a)(1) (emphasis added)

[4] MINERALS MANAGEMENT SERVICE, DRAFT PROPOSED OUTER CONTINENTAL SHELF (OCS) OIL AND GAS LEASING PROGRAM 2010–2015: CONSIDERING COMMENTS OF GOVERNORS, SECTION 18 FACTORS AND OCS ALTERNATIVE ENERGY OPPORTUNITIES 90 (2009) (emphasis removed) [hereinafter DPP].

[5] *Id.* at 91.

[6] *Id.* at 95.

[7] MINERALS MANAGEMENT SERVICE, OCS REPORT MMS NO. 2007-017, ECONOMIC ANALYSIS FOR THE OCS 5-YEAR PROGRAM 2007-2012: THEORY AND METHODOLOGY 1 (2007) [hereinafter ECON. ANALYSIS].

[8] *Id.*

[9] ECON. ANALYSIS at 3-4.

[10] *Id.* at 5

[11] *Id.* at 4, 9.

[12] *Id.* at 6.

[13] *Id.* at 17.

[14] DPP at 133.

[15] *Id.* at 96.

[16] *Id.*

[17] *Id*. at 136.

[18] DPP at 136.

[19] *Id.* at 135.

[20] *Id.* at 135.

[21] GORDON SICK, SALOMON CTR., MONOGRAPH SERIES IN FINANCE AND ECONOMICS NO. 3, CAPITAL BUDGETING WITH REAL OPTIONS (1989); A.K. Dixit, *Entry and Exit Decisions under Uncertainty*, 97 J. POL. ECON. 620-638 (1989); S. Majd & R.S. Pindyck, *The Learning Curve and Optimal Production under Uncertainty*, 20 RAND J. ECON. 331-343 (1989); P. Bjerksund & S. Ekern, *Managing Investment Opportunities under Price Uncertainty: from Last Chance to Wait and See Strategies*, 19 FIN. MGMT., Autumn 1990, at 65-83; TOM E. COPELAND ET AL., VALUATION - MEASURING AND MANAGING THE VALUE OF COMPANIES (1990); D. LUND & B. ØKSENDAL EDS., STOCHASTIC MODELS AND OPTIONS VALUES (1991); R.S. Pindyck, *Irreversibility, Uncertainty, and Investment*, 29 J. ECON. LITERATURE 1110-48 (1991); L. Quigg, *Empirical Testing of Real Option-Pricing Models*, 48 J. FIN. 621-40, (1993); A.G.Z. Kemna, *Case Studies on Real Options*, 22 FIN. MGMT., Autumn 1993, at 259-70; Lenos Trigeorgis, *Real Options and Interactions with Financial Flexibility*, 22 FIN. MGMT., Autumn 1993, at 202-24; Han T.J. Smit & L.A. Ankum, *A Real Options and*

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[27] The Real Options Soc'y has been holding annual conferences since 1996. *See* www.realoptions.org.

[28] For example, if multiple leaseholders could potentially access the same reserve of oil, there would be an incentive to drill inefficiently early.

[29] Jeff Strnad, *Taxes and Nonrenewable Resources: The Impact on Exploration and Development*, 55 S. METHODIST U. L. REV. 1683 (2002).

[30] A put option allows the holder to *sell* an instrument at a fixed price. This is valuable when the underlying instrument is trading at a lower value than the exercise price.

[31] *See* Appendix.

[32] Robert Hahn & Peter Passell, *The Economics of Allowing More Domestic Oil Drilling*, (Reg-Markets Center, Working Paper No. 08-21 2008).

[33] While the perpetual American option comes close to simulating natural resource extraction decision, it is not perfect. There are some formal issues that arise because perpetual options on petroleum reserves cannot be freely traded on markets. Many real options models are based on the assumption of free tradability and estimate option value by constructing portfolios of assets that are traded. Non-tradability, along with risk-aversion, creates an incentive to exercise early. Some important theoretical work has been done on these issues, which would be taken into account in a full analysis. *See* Ashay Kadam, Peter Lakner, & Anand Srinivasan, *Perpetual Call Options with Non-Tradability*, 26 OPTIM. CONTROL APP. METH. 107 (2005).

[34] *See* Appendix.

[35] There is some controversy over whether natural resource prices follow Brownian motion with upward drift or are mean reverting. This is one of several technical questions that MMS would be required to address to incorporate an options framework.

[36] Lester R. Brown, *Is World Oil Production Peaking?,* Earth Policy Institute (Nov. 15, 2007), https://www.earth-policy.org/Updates/2007/Update67.htm (data from table, Crude Oil Price, 1970-2007, *available at* https://www.earth-policy.org/Updates/2007/Update67_data2.htm#table4).

[37] Timothy J. Considine & Donald F. Larson, *Uncertainty and the Convenience Yield in Crude Oil Price Backwardations*, 23 ENERGY ECON. 533, 535 (2001).

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[39] Hahn & Passel, *supra* note 32.

[40] DPP at 135.

Appendix

Black-Scholes formula:

$$C = S\Phi(d_1) - Ke^{-rT}\Phi(d_2)$$

where:

$$d_1 = \frac{\ln\left(\frac{S}{K}\right) + \left(\frac{r+\sigma^2}{2}\right)T}{\sigma\sqrt{T}}$$

$$d_2 = d_1 - \sigma\sqrt{T} .$$

S= current price

K= strike price

T= time to expiration

r= risk free rate of return

σ= volatility

D-P threshold price model:

$$V^* - I = \frac{V^*}{\mathrm{B}} \Leftrightarrow V^* = \frac{\mathrm{B}}{\mathrm{B}-1} I$$

Where V* is the trigger value, I is the initial investment, and β is:

$$\mathrm{B} = \frac{1}{2} - \frac{r-\delta}{\sigma^2} + \left(\left[\frac{r-\delta}{\sigma^2} - \frac{1}{2}\right]^2 + \frac{2r}{\sigma^2}\right)^{1/2} .$$

δ = convenience yield