Record: 1

Title: A risk analysis of oil development in the Arctic National...
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Source: Energy Journal. 1991, Vol. 12 Issue 3, p55. 22p. 1 Chart, 4 Graphs.
Document Type: Article
Subject Terms: *Petroleum -- Environmental aspects
Arctic National Wildlife Refuge (Alaska)
Geographic Terms: Alaska
United States
NAICS/Industry Codes: 424720 Petroleum and Petroleum Products Merchant Wholesalers (except Bulk Stations and Terminals)
486110 Pipeline Transportation of Crude Oil
424710 Petroleum Bulk Stations and Terminals
211111 Crude Petroleum and Natural Gas Extraction
412110 Petroleum and petroleum products merchant wholesalers

Abstract: Presents a risk analysis of the effects which oil development will have on the Arctic National Wildlife Refuge (ANWR) in Alaska. Information on ANWR; Report from the Department of Interior on the wildlife resources of the region; Previous studies on ANWR's oil potential; Environmental assets of the region that could be put at risk by oil development.

Full Text Word Count: 8954
ISSN: 0195-6574
Accession Number: 9610284498
Database: Academic Search Complete

A RISK ANALYSIS OF OIL DEVELOPMENT IN THE ARCTIC NATIONAL WILDLIFE REFUGE

The Arctic National Wildlife Refuge (ANWR) in Alaska is simultaneously the most promising onshore area for oil exploration and one of the wildest areas remaining in the USA. The conflict between the need to develop energy resources and the desire to preserve wild areas has led to a prolonged debate over the merits of programs to lease the region for oil exploration and development.

In this study we report on a risk analysis of the oil potential of the ANWR. We develop a comprehensive simulation model of the oil exploration, development and production process in the ANWR based on publicly available data on the oil geology of the region. Compared to existing models of the ANWR this model is unique in that it simultaneously takes into account the essential geologic characteristics of the region and the dynamic nature of the development process. The model projects the volume of oil production over time, oil industry profits and net national economic benefits, all in probabilistic terms.

The model provides a unifying framework for evaluating the limitations of previous models. It also allows us to better assess the potential role of the ANWR in future U.S. oil production, to evaluate the effects of policies that would mitigate environmental damage and, in general, to better frame the debate between advocates and opponents of development.

INTRODUCTION

The Arctic National Wildlife Refuge (ANWR) is a 19-million acre reserve in the northeast corner of Alaska, stretching from the Brooks Range in the south to the Beaufort Sea in the north and from the Canadian border on the east to the Canning River on the west. It was established in 1980 as a wilderness refuge by the Alaska National Interests Lands Conservation Act (ANILCA).[1] The coastal plain of the refuge, some 1.5 million acres in extent, has long been considered a region with high potential for oil and gas resources. The refuge boundary lies roughly 75 miles east of Prudhoe Bay, the site of the largest single oil field in the United States, and the northern terminus of the Trans-Alaska Pipeline System (TAPS), which carries North Slope oil south to the port of Valdez. While no subsurface exploration has occurred in the coastal plain,[2] there is reason to suspect that the geology which gives rise to large oil fields around Prudhoe Bay may continue across the coastal plain to the east.

In the light of this potential for oil and gas discoveries, the ANILCA legislation temporarily exempted the coastal plain from the prohibition on minerals exploration that is a normal part of wilderness refuge status. Section 1002 of ANILCA required the Secretary of the Interior to conduct baseline studies of the fish and wildlife populations, to develop guidelines for an oil and gas exploration program, and to prepare a report to Congress that would recommend whether further exploration, development and production of hydrocarbons should be allowed.

The resulting Department of Interior (DOI) report (Clough et al., 1987) presents a comprehensive review of the wildlife resources of the region and provides estimates of oil and gas potential based on a series of seismic surveys commissioned by DOI. The report concluded that the probability of successful commercial development of oil resources was 19%.[3] If any oil were to be produced, the mean amount was estimated to be 3.23 billion barrels. By comparison, annual U.S. consumption is over six billion barrels -- about half of which is produced domestically. The net present value to the nation (including business profits and transfers to governments) of potential ANWR oil production was estimated at $15 billion. The report also concluded that development could be constrained in such a way that detrimental impacts on the wildlife (and the environment generally) could be kept to an acceptable level. The recommendation of the Secretary of the Interior to Congress was to approve full-scale leasing of the ANWR.

Since the release of the DOI report a lively debate has taken place over ANWR leasing. Both the Reagan and Bush administrations have proposed opening the ANWR to development. In fact, one of the first political consequences of the grounding of the Exxon Valdez was the postponement of Congressional action on the issue. The issue resurfaced in early 1991 with the Bush administration including ANWR development as a key part of its post-Gulf War energy plan. ANWR development has consistently been opposed by spokesmen for the environment. Their position has generally been that any ANWR leasing program would lead to irreversible and catastrophic degradation of the ANWR environment and that increased efficiency in transportation and buildings would reduce hydrocarbon demand at lower cost than ANWR oil (see, for example, Watson, 1991).

The fundamental policy issue raised by the ANWR question is how to compare the economic benefits of development with the costs of environmental degradation. Not only is it difficult to measure these costs and benefits on a single scale, but both costs and benefits are highly uncertain. The uncertainty in the economic benefits arises from uncertainty as to how much oil is present in the region, how much of what is present will be profitable to recover, what domestic oil production and demand will be in the future and so on. The uncertainty in environmental costs is due to uncertainty over how the ANWR will be developed if leased, how development will affect the environment and how to evaluate different classes of environmental change. Radically different philosophies have been brought to bear on the question of measuring environmental damage. The DOI study, for example, takes the viewpoint that development is benign if the populations of key species are not significantly reduced. The common environmentalist viewpoint, on the other hand, is that development of any permanent facilities substantially degrades the value of the ANWR as a wilderness.

Policy analysis is further complicated by the unique status of the ANWR, which requires a special act of Congress before leasing can begin rather than a routine decision by a federal agency. This status automatically gives the ANWR decision a prominence it might not otherwise have and it encourages close scrutiny of the decision-making process. Most significantly, it makes inevitable a comparison of the ANWR decision to other federal energy decisions, such as those on conservation, renewable energy, auto-efficiency standards and so on. The often-repeated complaint against ANWR leasing is that other policies (such as improved auto efficiency) could provide as much or more energy to the economy at little or no environmental cost. Needless to say, it is extremely difficult to develop a credible comparison of policies as different as ANWR leasing and stricter auto-efficiency standards.

The purpose of this study is to develop a model of the ANW oil exploration, discovery and development process that can help to frame the debate on ANWR leasing. The paper is structured as follows. We first review the DOI study and a number of related studies. This review leads to a critique of the current state-of-the-art in modelling ANWR development. Following this critique, the structure of our simulation model is described and the geologic and economic data on which it rests are presented. We then present and analyze a base case run of the model, which uses parameters similar to those in the DOI analysis so that the results can be readily compared. Next we report the results of a set of sensitivity analyses in which we test the robustness of our results to changes in important parameters and in the underlying structure of the model. The paper concludes with a discussion of the implications of this research for the policy choices before Congress.

PREVIOUS STUDIES OF ANWR OIL POTENTIAL

Our purpose in this section is to review previous studies of the oil potential of the ANWR. The primary study is DOI's 1987 assessment but we also summarize the methods and results of a number of related studies. The section concludes with a critique of the current state-of-the-art in ANWR development modelling?

DOI Assessment

The Department of the Interior's assessment of the oil and gas potential of the ANWR 1002 region (Clough et al., 1987, chapter III) is based on geologic data collected specifically for this purpose consisting of surface geologic studies and a set of seismic surveys commissioned by DOI. The seismic data were collected only after an agreement was reached between the industry and DOI to keep the data confidential. These data were interpreted by DOI geologists in light of the known geology of the nearby Prudhoe Bay area and the National Petroleum Reserve further to the west. In DOI's view, the petroleum geology of the ANWR consists of seven plays, 26 prospects and 89 reservoirs (ibid., Table III-2). Figure 1 shows the location of the 26 prospects in the 1002 area. Clearly, these potential drilling sites share a small number of potentially oil-rich strata.

The general plan of DOI's methodology for estimating the oil potential of the ANWR was to first estimate resources at the play level and then estimate reserves at the prospect level. The resource assessment proceeded from a probabilistic description of the geologic parameters of each play. These parameters include the number of associated prospects, the volume of source rock, the density of oil per cubic meter and so on. Monte Carlo methods were used to combine these inputs into a probability distribution for oil resources for each play. The resulting estimate of mean total resources is 13.8 billion barrels, with a 5% chance of more than 29.4 billion barrels. Most of these resources are to be found in two plays, numbers 5 and 6, with small contributions expected from the remaining five plays. Most studies of the ANWR (including ours) accept these data as the fundamental description of the geology of the region.

The second phase of the DOI assessment uses the resource estimates just described to estimate the volume of oil that might be recovered and marketed from the region. This assessment uses the Monte Carlo simulation program Presto II (Cooke, 1985) which simulates an exploratory drilling program. Presto 1I uses much the same approach as was used to determine resources -- except that the focus is on prospects rather than plays. Each reservoir is sampled first to see whether it contains oil. For reservoirs that contain oil, the amount of resource present is then sampled. If this amount is below the exogenously set Minimum Economic Field Size (MEFS), the program treats it as zero. Resources above the MEFS are then added to give an estimate of total economic reserves. Finally, the economic inputs are used to evaluate costs and revenues to the developers, as well as tax and royalty payments to the state and federal governments. This modelling procedure does not take into account the sequential nature of development or the dependence of certain costs such as pipeline costs on the location of discoveries.

The DOI study also includes only the five largest prospects (out of 26 identified) in the Presto II analysis. The rationale given is that oil development would be economic in this remote region only if a large discovery were made and the largest prospects hold the greatest promise of a large discovery.

Among the many inputs to the Presto II model, the MEFS is one of the most critical. If the MEFS is set too high only rare, large fields will be developed; if it is set too low many small, uneconomic fields will be developed. A separate study was performed for the DOI assessment to determine an appropriate MEFS for the 1002 region (Young and Hauser, 1986). The authors developed a spreadsheet model for determining the profits of oil developers under a range of scenarios. They made assumptions about development schedules, investment and production costs, oil prices, inflation rates, and transportation costs, and determined the smallest possible field that would return a profit at a 10% real rate of discount. Their model looked at each of the 26 prospects separately, as if each had to bear the entire costs of creating the infrastructure necessary to move oil to the TAPS pipeline. Their results are obviously sensitive to many factors -- particularly future oil prices and the location of the discovery (whether on the eastern or western ends of the 1002 area). For an oil price in the year 2000 of $33 (1984 dollars), they estimate a MEFS of 425 million barrels for a field in the west and 575 million barrels for a field in the east. At an oil price of $40, the range is 150 to 200 million barrels, respectively, while at $22, the range is 1.4 to 2.0 billion barrels.

The results of DOI's analysis can be summarized as follows. First, DOI estimates a 19% chance that any oil will be produced from the ANWR. This probability is a function both of the geologic risk that little oil is actually present, and the economic risk that whatever oil is found will not be economic to produce. If economic quantifies of oil are found, the mean amount produced is estimated at 3.23 billion barrels. There is a 5% chance that more than 9.24 billion barrels will be produced. (By way of reference, the supergiant field at Prudhoe Bay will produce in excess of ten billion barrels of oil before it is depleted.) But focusing on conditional estimates of reserves, as some reports have, can be highly misleading. While the conditional mean is 3.23 billion barrels, there is an 81% chance that no oil will be produced. The least misleading single number from the DOI analysis for estimated economic reserves is 614 million barrels: the unconditional mean (19% of 3.23 billion barrels).s Likewise, the published figure of $14.61 billion for total economic benefits is conditional on development; the appropriate figure is the unconditional estimate of $2.28 billion.

The weaknesses of the DOI study include both the use of a number of questionable modelling assumptions and the failure to address several significant issues. The most important modelling assumptions are the exclusion of the 21 smaller prospects, the use of a MEFS based on a stand-alone analysis, and the assumption that prospect risks are independent. The study justifies excluding the smaller prospects on the grounds that development will be economic only if a large discovery is made. Yet the "smaller' prospects actually may contain absolutely large amounts of oil and thus may contribute significantly to production in those scenarios in which a large discovery is also made in one of the large prospects. The MEFS analysis assumes each prospect must pay all infrastructure costs, which again overstates the costs associated with development of a smaller prospect after discovery of a large field and subsequent development of infrastructure. Finally, the study assumes that prospect risks for prospects that share plays are statistically independent, which would seem to be implausible. One would expect that drilling a dry hole at prospect A, which shares one or more plays with prospect B, would raise the probability of a dry hole at B. Likewise, finding a play productive at A would raise the probability of success at B.

The most important issue not addressed in the DOI study is what the likely time path of oil production is from the ANWR. This information is vital to an assessment of the contribution ANWR oil can make to total U.S. production. It is also important for determining whether the TAPS will still be in operation during the time of ANWR production. Another omission of the study is a treatment of the most likely location of development. The form and amount of environmental damage may depend heavily on which of the 26 prospects are most likely to be developed. For example, the Porcupine caribou herd uses only part of the coastal plain for its calving. The consequences of dosing these areas to development to protect the herd cannot be determined from the study. Finally, the study treats uncertainty in economic assumptions (such as future oil prices) in only a cursory manner. It is impossible, consequently, to determine how sensitive the report's conclusions are to the specific assumptions adopted.

Related Studies

In 1986 the State of Alaska Department of Natural Resources released its estimate of oil resources for the ANWR 1002 region (Hansen and Kornbrath, 1986) based on essentially the same geologic information as the DOI study. The state report gives a probability distribution for oil-in-place that shows considerably smaller amounts of oil at all probability levels when compared to the DOI study. For example, the mean amount estimated by the state is seven billion barrels; the comparable figure from the DOI study is 13.8 billion. This difference is attributable primarily to a difference in the interpretation of the potential of a single play: the Ellesmerian (play 6 in the DOI study). The DOI study attributes to this play an average of 7.22 billion barrels -- more than half of total resources. The state study, by contrast, attributes only 1.13 billion barrels to this play.

W. Thomas Goerold of The Wilderness Society published several studies of the ANWR (Goerold, 1987 and 1988). In the first he subjects the DOI's estimate of Net National Economic Benefits (NNEB) to sensitivity testing, using a model similar in overall design to that of Young and Hauser. His results show a range of estimates for the mean present value of NNEB, depending on assumptions as to drilling costs, production costs and prices, from $.32 to $1.39 billion. These estimates are less than half DOI's estimate of $2.?8 billion. The differences can be attributed largely to the assumption of much lower oil prices ($18 vs. $33). In Goerold's second study a similar model is used to calculate the MEFS as a function of prices and costs. Again, he uses an oil price much lower than the DOI study's estimate, typically $16 with a 1% rate of growth. His results show a MEFS two to four times larger than the Young and Hauser estimates, typically ranging from 860 million to 3.26 billion barrels. At these levels for the MEFS, the probability of successful development drops to 11.$% from the 19% estimated by DOI.

In 1987 the Energy Information Administration (EIA) of the Department of Energy published its study of the ANWR problem in response to the DOI study. EIA accepted the DOI assessment of oil-in-place, but considered the estimates of economically recoverable oil too conservative. The reasons cited include the small number of prospects (five out of 26) included in the DOI simulations, the use of a high MEFS, and the use of high finding and development costs. Rather than work directly with these assumptions and revise DOI's analysis, EL& chose to make the heroic assumption that 25% of all oil-in-place will ultimately be recovered from the ANWR. The report argues that even this figure is conservative, since Prudhoe Bay is expected to reach nearly .50% recovery. The resulting estimate for unconditional reserves is 3.45 billion barrels[6] -- roughly five times the DOI f'igure of 614 million barrels. The EL& study also includes a projection of ANWR production over time (Figure 2). The results show ANWR production peaking 15 years after initial leasing at a rate as high as 25% of then-current U.S. production.

The Congressional Office of Technology Assessment (OTA) published a study early in 1989 that includes a critique of DOI's MEFS assumption. The authors cite six possible sources of bias in the DOI assessment of the MEFS: (a) inclusion of sunk costs in the calculation of the return to development; (b) each prospect is required to pay for all necessary infrastructure, even that shared among prospects; (c) outdated tax rules; (d) high development costs; (e) high oil prices and (f) inclusion of only the 26 known prospects as possible oil sources. The report claims that all of these biases, except that due to tax rules, lead to an underestimate of the oil potential of the ANWR. On this basis the OTA expresses the opinion that the DOI estimate of economically recoverable oil is biased downward. They do not, however, provide an estimate of how large this bias may be. They also point out that any error in estimating economic reserves may be dwarfed by errors in estimating the underlying mount of oil-in-place in light of the wide disparities between the State of Alaska estimates and those of the DOI.

Summary of Literature

In the preceding sections we have reviewed the major studies of ANWR development from the points of view both of methodology and conclusions. The first observation that emerges is the extent of controversy over the fundamental geological potential of the region. The two available estimates of oil-in-place differ by 100% and most of this difference is attributable to a single play. Since the raw data behind the various estimates are not available to the public, one has to accept either the State of Alaska's estimate of seven billion, or DOI's estimate of 13.8 billion barrels of oil-in-place. This a huge difference and the uncertainty created by it is not likely to be resolved soon.

A second observation is that the modelling that has been done of the exploration, development and production process has focused heavily on the exploration stage. Both the DO! and Goerold studies attempt to estimate total production, but not the time path of production. Neither attempt to model the complete exploration, development and production sequence and the many decisions the oil developers will have to make during the process. Only the EIA attempted to project production over tune and they did so using a quite unsophisticated model combined with overly optimistic assumptions.

Finally, we observe that the most sophisticated treatment of the geology and economics of the ANWR, the DOI study, is itself based on several strong assumptions including a limited number of prospects, a MEFS biased by the assumption that each prospect must support all infrastructure, and independence in prospect risks. The report does not offer sufficient information in the form of sensitivity analyses to judge whether or not these assumptions are harmless. Certainly they reduce the credibility of the study.

This review of the model-based literature on ANWR leads to the conclusion that existing studies are either methodologically sophisticated analyses of a restricted aspect of the problem, such as the DOI study, or unsophisticated reports on the full range of relevant issues, such as the EIA study. Moreover, most of the studies are not repeatable because either the data or the methods behind them (or both) are not fully divulged. There is no single, comprehensive study of ANWR development which has a methodology that is fully transparent to the public. This is the gap this paper attempts to fill. We develop a comprehensive model that takes all the available information into account and provides consistent projections of oil production from the ANWR over time. The model allows us to test the major assumptions of previous models and to provide a fuller picture of the choices facing the country in the ANWR.

DESIGN OF AN ANWR DEVELOPMENT SIMULATION MODEL

Modelling Goals

The overall goal of our research was to develop a realistic model of the development process in the ANWR, from exploration through production, utilizing the available geologic and economic information. As we have seen, none of the previous studies has made full use of the geologic data available especially on the location of prospects), nor have they modelled the decision-making processes oil developers are likely to go through as they develop the 1002 region. One of the contributions of our model, then, is to offer a more disaggregated and comprehensive model of the linkage between the underlying geology of the region and possible development patterns. Another contribution of the model is insight into the likely location of development and the impacts on oil production and profits of policies restricting leasing to certain portions of the 1002 region. A further contribution lies in the ability of the model to forecast oil production over time. These projections are fundamental to many of the policy questions surrounding ANWR development. Finally, because the model is more general and flexible than previous models, we can use it to test the importance of key modelling assumptions in earlier studies.

Overview of Model Logic

The model is based on a reservoir-level description of the underlying geology of the ANWR, which is the most disaggregated approach possible given the available data. Following the DOI study, we assume all oil in the ANWR is contained in 89 reservoirs. These traps share seven plays and 26 prospects. Development can occur only at one or another of the prospects but the information gained by drilling may influence results elsewhere because many prospects share plays. We include all 26 prospects in our simulation, not just the largest five as in the DOI study. The details of our derivation of probability distributions for oil-in-place by reservoir are given below.

Given this description of the geology, the model proceeds as follows. First, a random sample is taken from the probability distribution for oil-in-place for each reservoir (prospect-play combination). The amounts of oil discovered in this process are then aggregated to the prospect level. We then apply a prospect risk factor that determines whether each prospect is wet or dry. Next we rank the prospects in the order of total oil discovered. We then apply a MEFS to eliminate prospects too small to develop. The resulting set of prospects is then developed in order of size (largest to smallest), using a set of assumptions as to the time needed to develop a prospect, the time between development of successive prospects and so on. As part of this process the model determines the (approximately) minimum cost pipeline network required to bring oil from each developed prospect to TAPS. Finally, the economic results of this development sequence are worked out by modelling production over tune from each prospect, accounting for the associated development and production costs, taxes and so on. The outputs of the model include probability distributions for total oil production, production over time, the likelihood of developing each prospect, revenues to oil developers, and taxes to the state and federal governments.[7]

The assumption that prospects will be developed in order of size is based on the theoretical proposition that this pattern of development is characteristic of an optimal plan. It is also supported by empirical evidence that on average the largest fields in an area are discovered and developed first. The use of a MEFS in this model may seem out of place, given our comments earlier on the inappropriate use of the concept in related models. As we see the development process, the minimum economic field size is an ever-changing quantity depending on the particular sequence of discoveries that have occurred and on their locations. Thus, the discovery of a 400-million barrel field in the western part of the 1002 area could be subeconomic if it was the only field discovered but economic if it followed the discovery of a giant field in the east. Thus the use of a single, fixed MEFS inevitably distorts the actual development process. However, we plan from the start to treat the MEFS as a parameter and to allow it to vary across a set of simulations in order to determine the be. st (fixed) MEFS. This procedure is still a simplification because it assumes a constant MEFS. There may be a time-varying MEFS which would lead to higher profits for the developers.s It is, however, a practical and reasonably realistic approach.

Derivation of Oil-in-Place Distributions

The oil-in-place distributions for each of the reservoirs in the model were derived from data in the DOI report. That document gives probability distributions for oil-in-place for each of the seven key plays in the ANWR (Figure III-15, p. 77). It also gives the areal extent of each of the 26 prospects and the plays associated with each prospect (Table III-2, p. 69). Unfortunately, the plays used in the description of oil resources do not match the plays used in the description of the prospects.[9] Some assumptions were required to connect the play and prospect data. The key assumption was that prospects that can reach play 6 (Folded Ellesmerian) can also reach play $ (Imbricate Fold Belt), since play 5 is omitted from the prospect table. This assumption is justified on the grounds that both plays cover the same portion of the eastern 1002 area (see Figure III-12, p. 71).

The DOI report does not reveal directly the resource potential of each reservoir. We developed estimates for each reservoir by allocating play resources to prospects in proportion to the prospect's area1 extent since, on average, prospects with a larger area will have a greater resource potential. The details of the method are as follows. First, we fitted a lognormal distribution to each of the play resource distributions. We calculated the share each prospect has in the play by computing its area as a proportion of the total area of all prospects in that play. We then created a lognormal distribution for resources at each play-prospect combination by multiplying the play mcan and standard deviation by the prospect's areal share. Finally, we successfully tested the consistency of this procedure by sampling from all the prospects in each play and verifying that the resulting distribution of total oil-in-place for that play matched the original play distribution. Thus the total amount of oil to be found in all the reservoirs of a given play matches the resource potential of the play as given by the DOI.

Economic Parameters

In addition to geologic inputs, the model requires a number of economic assumptions. Our approach to the determination of these inputs for a base case run was to match as closely as was practical the assumptions of the DOI study, not because these assumptions are necessarily the most reasonable but so as to reduce the sources of difference between our initial results and the DOI results. Sensitivity analysis can then be used to test the robustness of the implications of the model to any of these inputs. The most important inputs are given in Table 1.

Most of our cost data come from Young and Hauser (1986) which updates the estimates in the definitive National Petroleum Council study of 1981. As Goerold (1987) points out, petroleum production costs (like petroleum prices) are highly volatile, so the best estimates of any one year may not accurately forecast the future. Since costs and prices affect the model in roughly symmetrical and opposite ways, we will use our sensitivity analysis (reported below) of prices to stand for analysis of the sensitivity to costs. Data on development timing come primarily from the DOI and OTA studies, and to a limited extent from Young and Hauser.

Base Case Results

This base case is not meant to be a most likely case, nor is it our forecast. It is designed to mimic as closely as possible the assumptions of the DOI analysis in order to facilitate comparison. In later sections we will discuss the sensitivity of the model to changes in the key parameters.

Given the structure of the model, the key parameters are the MEFS, the prospect risk and oil prices. The MEFS is simply a minimum discovery size below which discoveries are treated as dry holes. It is set at 440 million barrels in both the DOI report and our base case. The prospect risk is the probability that a given reservoir will contain no oil. In the DOI analysis it apparently was in the range from .90 to .95; that is, each prospect carried a probability of 90% or higher of being dry? For our base case this risk is set at 90%. Finally, oil prices are set at $33 per barrel rising at 1% per year in both studies.All calculations are done in constant dollars with a 10% discount rate.

We first focus on the net present value of revenues to the oil developers after all costs and taxes have been paid. Our model shows a mean value of net revenues of $1.58 billion. In the 5,000 trials of the simulation, the minimum value recorded was -$1.03 billion and the maximum was $98.52 billion. The probability the developers suffer a loss is about 5%; in 50% of the trials they make nothing and in 45% they earn positive revenues. The DOI study does not report net revenue estimates separately so direct comparisons are not possible.

Net national economic benefits (NNEB) are defined as the net present value of revenues to the developers plus the net present value of all taxes and royalties. For the base case the mean value for NNEB was $3.43 billion, with a maximum of $197.57 billion and a minimum of $-1.49 billion. The probability distribution for NNEB is strongly skewed to the right, with the 95th percentile value ($17.76 billion) quite small relative to the maximum value. The DOI study reports an estimate of NNEB conditional on development of $14.61 billion. With a 19% probability of development, this translates into an unconditional value of $2.78 billion, which is the same order of magnitude as our result.

Total oil production in the base case averages 1.14 billion barrels, with a minimum of zero (which occurs on 50% of the trials), and a maximum of 42.87 billion barrels. The DOI analysis shows a much higher probability of no oil production (81% vs. 50%), and a comparable conditional mean value (660 million rs. 557 million). However, the maximum amount of oil simulated by the DOI was 22 billion barrels --about half the amount we report.

Oil production over time is displayed in Figure 3. This figure shows the mean level of oil output dropping from a high of 100 million barrels in the first year of production to 26 million after 15 years. The figure also conveys a sense of the probability distribution of annual output by showing the time path of the 95th percentile of the output distribution for each year. These results can be compared to the EIA projections of oil output (Figure 2). The EIA projections show a maximum annual rate of output of some :550 million barrels for the high recovery case of 7.35 billion barrels. Our results are far less optimistic. For our model the 95th percentile of the distribution of oil output in the maximum year is only 420 million barrels. However, the maximum output is 4.4 billion barrels. Once again we see that with a very small probability a huge amount of oil may be discovered and produced from the ANWR.

Twelve of the 26 prospects have a probability of development in excess of 1%. The four most likely prospects are located in the eastern side of the 1002 area. They are also generally the largest prospects by surface area. Three of the four (19, 20 and 21) are associated with play 6, which is the disputed Ellesmerian play. It follows that if one were to adopt the State of Alaska's view of ANWR geology, in which the Ellesmerian has far less potential, both the total amount of oil one would expect and the location of probable discoveries would shift dramatically. In fact, under the state's interpretation of the geology, the case for development loses most of its force.

In summary, we find that when we run our model in a manner that closely approximates the DOI model, we get a picture of ANWR development that is different from that provided by DOI in several important respects. Although our estimates of mean oil production are similar to DOI's, we find both a considerably lower probability of no production (50% vs. 81%) and a substantially higher maximum value (43 vs. 22 billion barrels). We also find that the most important prospects are those involving the Ellesmerian play, which the State of Alaska determines to be much lower in potential than does DOI. Our results, therefore, highlight the importance of this assumption to the DOI conclusions.

FURTHER RESULTS

In this section we report on additional experiments with the model that allow us to determine the robustness of our model to key assumptions and to test the significance of several of the most questionable assumptions of the DOI study. We focus on five aspects of the model: the MEFS, oil prices, prospect risks, exclusion of small prospects and restrictive leasing.

Minimum Economic Field Size

Previously we observed that the assumption of a fixed MEFS is a rough way to model the changing determinants of the economic viability of a particular discovery in time and place. One way to test the significance of this assumption is to run the model over a range of values for the MEFS. In Figure 4a we plot the net present value of revenues to the oil developers as a function of the MEFS. The figure shows that revenues to the developers are negative for very low minimum field sizes; this is a result of too many small discoveries being developed. Likewise, at a very high MEFS revenues are low', this is due to the development of only the rare huge discoveries. Revenues rise with the MEFS up to a maximum value of about $1.60 billion at a MEFS of 800 million barrels. Figure 4b shows that the probability of development is quite sensitive to the MEFS. At our base case level of 440 million barrels the probability of development is 50%; it falls to 30% at one billion barrels and to 17% at two billion barrels. As we have seen, due primarily to the inclusion of smaller prospects, the probability of development according to our model is considerably higher than the DOI projections. These results show that the likelihood of development remains substantial at any reasonable MEFS. To the extent that the MEFS accurately foretells the behaviour of private decision makers, these results indicate that the chances are high that a leasing program will eventually lead to some development of the ANWR.

Oil Price

Over a range of oil prices from $15 to $60 per barrel,[11] a developer's mean revenues increase from -$.9 to $4.24 billion. At $15, revenues range from a minimum of -$2.86 billion to a maximum of $2.17 billion. At $60 the range is -$.98 to $239.52 billion. At low prices (and with an MEFS of 440 million barrels) losses are highly likely. Even at high oil prices there is a small chance of a loss, but also some chance of huge returns. The range for net national economic benefits closely tracks the results for revenues.

Prospect Risk

Prospect risk is the probability that a given prospect is a dry hole. In the DOI study, the prospect risk for each of the five included prospects was roughly 93% and the risks from prospect to prospect were assumed to be probabilistically independent. In order to test the sensitivity of the model to dependence in prospect risks, we modelled an extreme case in which the correlation between prospects sharing a play was one. For this purpose each play was considered as a unit. In the simulation process we arbitrarily picked one prospect in a play and sampled to determine whether or not it contained oil. If it did, then all other prospects in that play were taken to be oil-bearing as well. Likewise, if the first sample was dry all other prospects in that play were taken as dry.

The results arc somewhat surprising. Dependence in prospect risks does have a significant impact on the probability of producing no oil, increasing it from 50% to 75%. However, the expected value of oil production changes only slightly, from 1.14 to 1.13 billion barrels, because dependence increases the probability of large discoveries. Average producers' revenue also shows little change but the maximum value of revenues drops from $100 to $67 billion. Dependence in prospect risks has the effect of narrowing the range of outcomes for revenues, reducing both the extremely low and high values, in such a way that the overall expected value is essentially unchanged. We conclude that dependence in prospect risks has little effect on the average return to development but substantially reduces the attractiveness of ANWR development by reducing the maximum possible returns.

Exclusion of Smaller Prospects

The DOI study based its estimates of the potential of the ANWR on the five largest prospects in the region. These five are not identified, but a plausible guess is that the top five were those with the largest surface areas: prospects 18, 19, 20, 21 and 1. Our earlier results show that these are also the prospects with the highest likelihood of being developed. To test the impact of this DOI assumption we ran the model with the potential of all prospects other than these five set to zero. The average amount of oil produced in this case was 830 million barrels, down from the base case amount of 1.14 billion, and the probability of no development rose from 50% to 60%. But the real impact of the DOI assumption is not on the average amount of oil produced but on the maximum -- which drops by almost haft from 43 billion barrels in the base case to 23 billion in this case. Eliminating the smaller fields from the analysis, then, creates only a modest bias in the estimate of the average amount of oil to be produced but introduces an enormous bias in the upper limit on production. The same observations can be made as to the effect of the DOI assumption on estimates of the returns to both developers and the nation as a whole.

Restrictive Leasing

The DOI study identified the Porcupine caribou herd as one of the most significant environmental assets of the region that could be put at risk by development. This herd migrates annually from Canada into the 1002 region for calving. It makes especially heavy use of the southeastern part of the coastal plain, where prospects 20, 21, 22, 24 and 25 are located. Of these five prospects only 20 and 21 are of significant size. Our earlier results indicated they would be developed with a probability of 7-89'0. When run with these prospects excluded, our model shows an average production of 770 million barrels -- a drop of 34% from the base case. The loss in revenues to the developer is of the same relative magnitude: $1.02 billion in present value vs. $1.58 billion in the base case. The maximum value of revenues also drops from $99 billion to $70 billion. We conclude that a policy which excludes these prospects would have a substantial negative impact on the overall economic value of developing the ANWR. Whether this loss is offset by the environmental benefits gained is beyond the scope of this study.

SUMMARY AND POLICY IMPLICATIONS

In this paper we have presented an original simulation model of the oil exploration, development and production process in the 1002 region of the Arctic National Wildlife Refuge. The model is designed to assist in the evaluation of the potential of the ANWR and to test the basic assumptions that limit earlier modelling efforts. Our key conclusions are the following:

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1. the ANWR has a significantly higher maximum potential for
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oil production than previously thought, and mean production, about 1.14 billion barrels, about tuftee previous estimates;

2. our results show a 50% chance of significant development following leasing; this is much higher than the DOI estimate of 19%;

3. our results highlight the importance of the Ellesmerian play to the potential reported by DOI; if one accepts the State of Alaska's more pessimistic interpretation the overall potential of the region falls by at least a half;

4. while earlier studies have been criticized for using a too high or too low MEFS, our study shows the potential of the region to be insensitive to the MEFS over a wide range;

5. exclusion of smaller prospects substantially reduces the maximum amount of oil one can expect while having relatively little impact on the mean amount of oil;

6. dependence in prospect risks also substantially reduces the maximum amount of oil one can expect from the region while having relatively little impact on the mean amount of oil.

While the primary focus of this paper has been on modelling ANWR development, the ultimate purpose of modelling is to inform the policy debate. A few observations on the implications of our results for policy are therefore in order.

The overall conclusion that should emerge from this study is that the uncertainties surrounding ANWR development are even more extreme than previous studies have indicated. First, there is a fundamental difference in interpretation of the basic geology of the region which changes the geologic potential by 100%. Second, our model shows that even if we accept the more optimistic interpretation of the geologic potential, the maximum amount of oil one could hope for is some 50 times higher than the mean amount, reflecting the probabilistic nature of the exploration, discovery and production process itself. Third, the oil prices that prevail in the oil market over the next several decades will determine the ultimate profitability of any oil produced from the ANWR: if oil prices remain in their recent range of around $20/barrel, almost no foreseeable discoveries will be economic. Thus profitable development of the ANWR rests on a significant oil price increase over the next ten or 20 years. Fourth, ANWR development will have unpredictable effects on the environment and the only way to fully ascertain what those effects will be is to make the irrevocable decision to develop. Finally, ANWR development competes in the energy policy arena with a number of other policies each of which has its own peculiar costs, benefits and uncertainties, making it difficult if not impossible to determine whether ANWR leasing is better than competing policies.

In its simplest terms, the argument for ANWR leasing rests on the enormous oil potential of the region, however small the probability of achieving this potential is. If there were no environmental consequences to development, it is hard to imagine any real debate over the merits of an immediate leasing program. But the potential environmental consequences, at least in the eyes of certain members of the public, are as enormous as the oil potential is in the eyes of wildcarters. No economic study can settle this debate which rests essentially on a dash of values. However, we believe a logical argument can be made for the position that ANWR leasing should take a back seat to another class of policies.

This argument starts with the realization that the environmental costs of ANWR development include some elements that are essentially certain, as well as elements that are uncertain. The uncertain elements (on which the DOI study concentrates) include the unpredictable effects on the number and health of certain important species in the region: the Porcupine caribou herd especially, but also the other mammal and bird populations. In assessing the risks to these species it is certainly relevant to study the effects of the development of Prudhoe Bay on related populations. It has been argued, for example, that because the caribou herds around Prudhoe Bay appear to have increased in number, development there has actually improved the environment. But there is another important viewpoint from which all development is environmentally damaging simply because it alters the pre-existing (nearly completely) wild state of the region. For those who value the region precisely because it is undeveloped, even development that would increase the numbers of some populations would be seen as damaging. In other words, the region is not valued because it supports 180,000 caribou but because it is wild and happens to contain caribou. The environmental cost of development, when seen in this light, is not uncertain at all. It is a valid concern, of course, as to how significant a fraction of the population shares this viewpoint. The strength of the environmental opposition to ANWR development would seem to offer a strong indication that this is more than a fringe view.

If we accept the point that ANWR development carries certain and substantial environmental costs, at least for a significant segment of the population, we see that the decision to lease the ANWR is an all-or-nothing decision. As the vast literature on option values (see Fisher and Hanemann, 1987) establishes, irrevocable decisions (especially those affecting the environment) generally require a higher ratio of benefits to costs than reversible ones. In addition, the benefits from ANWR development (if any) will be delayed eight to 15 years due to development lags and will be temporary. In contrast, the major competing policies, such as improved auto fuel efficiency, are not irrevocable decisions, provide essentially immediate gains (and costs) and have permanent benefits. This is not to say that these policies are clearly to be preferred to ANWR development -- the policy issues are not nearly that simple. What this argument does establish is that the policy of ANWR leasing carries certain unique costs which distinguish it from competing policies, and an appropriate evaluation of energy policy as a whole should take these costs into account.

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1. A nine million acre Arctic National Wildlife Range was created in 1960 for the purpose of preserving unique wildlife, wilderness and recreational values. The refuge created in 1980 includes the former range.

- 2. A single exploratory well was drilled by Chevron in 1987 on Alaska natives' land just outside the northern boundary of the ANWR The results of this exploratory well have not been made public.
- 3. Although large quantifies of natural gas are thought to be present in the area, it was determined that high transportation costs would prevent commercial exploitation in the foreseeable future. Accordingly, we will not discuss gas potential further here.
- 4. A brief glossary of geologic terms follows. Resources or oil-in-place is the amount of oil estimated to be present below the surface of a region. Reserves or economically recoverable oil is the amount of oil-in-place that can be recovered economically. A play is a horizontal stratum that has potential for bearing oil. A prospect is a region on the surface from which oil-bearing strata can be reached. A trap or reservoir is a three-dimensional region below the surface (a particular combination of play and prospect) that may hold oil.
- 5. For further discussion of these issues see Powell, 1990.
- 6. Unconditional and conditional reserves are identical in the EIA study since the probability of no production is zero by assumption.
- 7. The model is available from the author. It utilizes Lotus 1-2-3 and @Risk.
- 8. Ultimately, the optimal MEFS would vary not only with time but with the volume and location of previous discoveries. A full dynamic programming formulation of the model, in which a variables MEFS could be determined, is computationally intractable.
- 9. This is a result of the censoring that was required to keep the basic geologic data proprietary.
- 10. The DOI study estimates the area risk, which is the probability that all five prospects considered are dry, at 70%. This is roughly (.93) [5].
- 11. The oil price growth rate is zero in these cases.

GRAPH: Figure 2. Total U.S. Oil Output and Potential ANWR Output

GRAPH: Figure 3. Base Case Oil Production Over Time

GRAPH: Figure 4a. NPV Revenues as a Function of MEFS

GRAPH: Figure 4b. Probability of Development as a Function of MEFS

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Table 1. ANWR Model Inputs

Costs
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Transportation	$10.00/bbl	
Production	$3.00/bbl	
Exploratory Well	$20 million/well	(8 per prospect)
Development Well	$6 million/well	(160 per prospect)
Facilities	$500 million/facility	(4 per prospect)
Pipeline	$20 million/mile	
Royalty Rate	17%	
Federal and State Tax	50%	

Production Rates

10% of reserves first year
10% decline per year

Development Lags

First Prospect	9 years from leasing
Successive Prospects	4 years between prospects

MAP: Figure 1. ANWR Prospect Locations

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