Alternatives to Conventional Crude Oil: When, How Quickly, and Market Driven?

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Abstract

We examine the effect of uncertainty concerning remaining supplies of conventional crude oil and its production path on: the date alternative fuels will be needed, the quantity of alternative fuels needed, and how this uncertainty affects firms' willingness to provide alternatives in a timely fashion. Despite large uncertainties about the quantity of oil that remains and its production path, the start date for replacements is likely to fall within a twenty year period. Regardless of the exact start date, large quantities of replacements will be needed within a decade. Yet, these replacements are not likely to be available when needed because uncertainties about supply and its production path create an externality that generates an asymmetry in the strategy that maximizes the welfare of firms and society.

Introduction

The end of the Asian financial crisis started a significant turnaround in the world oil market. After more than a decade of stable or falling real oil prices, stagnant demand, and declining OPEC production, these indicators turned upward. Demand for crude oil rose from about 74 million barrels per day (mbd) in 1998 to nearly 84 mbd in 2005. Despite significant increases in output by non-OPEC producers, increased demand for crude oil raised capacity utilization by OPEC nations from about 90 percent in 1998 to about 99 percent in 2005. This rise is partially responsible for an increase in real oil prices from about \$10.42 per barrel in 1998 (1996 dollars) to \$39.91 in 2005 (Kaufmann *et al.,* 2004).

Further increases in oil demand and real oil prices depend in part on future production of crude oil and alternatives to conventional crude oil. If significant quantities of conventional crude oil remain, and if OPEC nations are willing to increase production (Kaufmann *et al.*, in review), increased output could satisfy demand from growth in oil-using capital stock and alleviate upward pressure on prices. Alternatively, if oil-using capital continues to grow but the quantities of crude oil that remain are limited, and the market does not generate significant quantities of alternative fuels, real oil prices may continue to rise.

The quantity of conventional crude oil that remains is uncertain. At the extremes, some argue that more than half of the world's supply of conventional crude oil has been discovered and/or produced while others argue that the correct percentages are less than a quarter. Uncertainty remains despite more than fifty years of debate because both sides can claim significant successes and point to important failings by the opposition. Several analysts argue that global production of crude oil has already peaked, or may peak soon (e.g. Campbell, 1998; Deffeyes, 2005). Their results are based on a methodology developed by Hubbert (1956), who successfully forecast the peak in oil production in the lower 48 states of the US more than a decade before it occurred, at a time that production had increased steadily for nearly fifty years.

Opponents argue that Hubbert's methodology cannot be applied to the world as a whole. They point out that the production paths for most nations do not follow Hubbert's bell-shaped curve and that many of the results marshaled in support of this curve are not supported statistically (Lynch, 2003). Instead, they argue that considerable quantities of crude oil remain, and this oil will be produced as political and economic conditions permit. In short, raising oil prices will generate increased supply. They point to new discoveries and increased production in non-OPEC nations such Mexico, Norway, and the United Kingdom following the 1973-1974 and 1979-1981 price spikes. Opponents argue that the price supply response is limited. They point out that the National Petroleum Council (1971) and MIT Energy Laboratory (1974) predicted significant increases in US oil production if real oil prices were to increase beyond some threshold. Although prices exceeded these thresholds in the 1970s and 1980s, production in the lower 48 states continued to decline.

We explore the significance of differences between these two camps regarding estimates for the quantity of crude oil that remains. Using a simple methodology, we identify dates for a peak in global oil production that are associated with a wide range of assumptions regarding the quantity of oil that remains, the rate at which oil demand increases, and the rate at which production declines following a peak. Despite vast differences in these estimates, the date for the global peak in production can be narrowed to a twenty-year window, 2010-2031.

This window seems far off, but its specter raises two critical questions. Following the peak, how quickly will the production of alternative fuels need to increase and will a competitive market make alternatives available in a timely fashion without significant government intervention? Our results indicate that regardless of the date at which global production of crude oil peaks, large quantities of replacements will be needed within a decade. Sufficient quantities of replacements are not likely to be available when needed because uncertainties about supply and its production path create an externality that generates an asymmetry in the strategy that maximizes the welfare of firms and society. In short, private firms reduce their risk by scheduling investments to produce alternative fuels after the anticipated peak in global oil production while society prefers a schedule that generates alternatives before the anticipated peak to avoid a large drop in welfare that would occur if supply dropped relative to the demand implied by the existing capital stock.

These results, and the methods used to generate them are described in four sections. In section II, we describe some of the techniques that have been used to forecast oil production. The third section describes a simple methodology that can be used to forecast a peak in global oil production based on production through 2004 and simple scenarios for the quantity of oil that remains and the rate at which production rises and falls. The results described in section IV indicate that uncertainty about the quantity of oil remaining and the rate at which production rises and falls moves the date at which global production peaks within a twenty-year window, 2010-2031. Should these forecasts be accurate, section V describes how large quantities of alternative furls will be needed within a decade of the global peak and that a competitive market s unlikely to generate these fuels in a timely fashion due to an asymmetry in the investment schedule that maximizes the welfare of energy-producing firms and society.

II Modeling Oil Supply and Production

Economic analyses of oil supply and production often are based on the Hotelling (1931) model of non-renewable resource extraction. Starting with information about the recoverable supply of oil, the cost of extraction, the demand curve, the model assumes that firms schedule production to maximize the net present of rents (the price of oil minus its marginal extraction cost). Simplifying assumptions allowed Hotelling to derive of a ‘rule’ for maximization—rents should rise with the rate of interest. This implies a production path in which output declines steadily over time if marginal extraction costs are constant or rises over time.

These price and production paths are inconsistent with observations for single nations or the world as a whole (e.g. Watkins, 1992). To rectify these inconsistencies, analysts have add real-world complexities, such as the difficulties of the exploration process, constraints on investment and capacity, ore quality, and a host of market imperfections. The modifications improve the ability of the Hotelling model to account for the historical record of the US oil industry, but the resultant complexity makes the optimal production and price paths specific to the assumptions (Krautkramer, 1998). As a result, there is a considerable literature that indicates that the theory-based Hotelling model cannot be used to project the production path for crude oil (Krautkraemer, 1998).

At the other extreme is an empirical methodology developed by Hubbert (1956). According to this methodology, cumulative discoveries and production can be modeled using a logistic curve, for which the asymptote represents the ultimate quantity of oil extracted, which is known as Q_∞. Hubbert (1956) used the bell-shaped first difference of cumulative production to forecast a 1971 peak in the lower 48 states. Although the forecast matched the 1971 peak in oil production in the lower 48 states, Hubbert (1980) admits that neither the logistic or bell-shaped curve is based on theory or the principles of petroleum geology, geophysics, or petroleum engineering. Consistent with this lack of theory, the accuracy of Hubbert's analysis was both luck and genius--if real oil prices or the quantity of oil shut in by the Texas Railroad Commission had evolved over some other path, Hubbert's forecast would have been less accurate (Kaufmann and Cleveland, 2001).

The element of luck may be responsible for the perennial failure of Hubbert's methodology to correctly forecast the peak in global oil production. For more than a decade, fitting Hubbert's curve to the historical data has indicated an imminent peak (e.g. Campbell, 1998). Each time the forecast date has been past without a downturn in production, the updated-curve suggests that the peak is soon to come.

The most important cause for this failure is the logistic curve's omission of economic and institutional factors. Oil demand grew by only about 17mbd between 1973 and 1998 due to higher oil prices and slower economic growth, compared to nearly 36 mbd between 1960 and 1973, when oil prices were low and economic growth was rapid (Figure 1). The logistic curve for cumulative production mistakenly interprets this demand driven slow-down in production as caused by resource depletion. This error causes two problems for empirical estimates of the logistic curve. The demand-driven reduction in production between 1979 and 1989 causes the curve to overstate production through 2004. For example, the "best fit" curve for Q_∞ equal to 1.8 trillion barrels indicates that 1.174 trillion barrels were produced between 1900 and 2004--only 0.985 trillion barrels were produced (Figure 1). By conflating the demand-driven reduction in production with resource depletion, stagnant demand also causes the methodology to understate the value of Q_∞ that best fits the historical record. For example, if the logistic curve is fit with a sample that starts after mass production of the automobile through 1973 (just before the first price shock), the value of Q_∞ that generates the best fit logistic curve is about 4 trillion barrels.

Despite these shortcomings, the accuracy of Hubbert's forecast was not pure luck—the methodology embodies an element of genius. Its general shape is consistent with an engineering truth about oil production. Oil production will not grow steadily and collapse overnight (Figure 1). The world will never wake to a headline, "The World Ran Out of Oil Today." Other than this, many production paths are possible. Production can rise and fall sharply or slowly, there can be one or more 'peaks,' and production can rise and fall at different rates. Regardless of the shape, the integral of the curve represents the total quantity of oil that can be extracted.

This constraint implies that we may be able to evaluate uncertainty about the quantity of oil that remains and the rate at which it will be produced with an empirical approach that starts with the observation that about one trillion barrels of conventional crude oil that have been produced through 2004 and that production in 2004 averaged 82.6 mbd. Starting with this level of depletion and production, we can project production paths that have a variety of shapes and that have integrals that correspond to a range of estimates for remaining oil supply. Comparing the results allows us to evaluate the effect of uncertainty about the quantity of oil that remains and the shape of the production path on the date at which global oil production peaks.

III Methodology

The methodology is designed to determine how uncertainty about the geological supply of crude oil and the economic and technical determinants of its production affect the year in which the global production of conventional crude oil peaks. To do so, observed rates of production between 1900 and 2004 are appended with curves whose integral corresponds to estimates for the quantity of crude oil that remains to be produced. Estimates for remaining oil supplies are gleaned from the literature and they are used in an algorithm that identifies the peak from a production path that can rise and fall at different rates.

Data

Historical data for the global production of crude oil production (including lease condensate but excluding natural gas liquids) between 1900 and 1959 are available from the American Petroleum Institute (1962). This time series is updated through 2004 with information from the Energy Information Administration (various years).

There is a long history of estimates for recoverable crude oil supply (Table 1). These estimates embody different assumptions about the geological resource base and the economic viability of technologies that are used to extract crude oil. These assumptions rarely are stated explicitly. Instead, we assume that large estimates for recoverable oil supply embody optimistic assumptions about the size of the resource base and the development and economic viability of advanced technologies to extract it while smaller estimates embody less optimistic assumptions about the resource base and the development and economic viability of advanced technologies to extract it.

Peer review literature and industry "grey literature" contain two types of estimates; ultimate recoverable supply and quantity of oil remaining. Ultimate recoverable supply refers to the total quantity of oil that will be extracted. As such, ultimate recoverable supply is defined as the sum of cumulative production, identified reserves, and undiscovered technically recoverable resources. Oil remaining refers to all of the oil that will be extracted beyond some date. As such, oil remaining includes identified reserves and undiscovered technically recoverable resources from a specific year. Notice that these categories are different from proved reserves. In the US proved reserves include quantities of conventional crude oil that are known to exist with certainty and can be recovered under current technological and economic conditions. As such, proved reserves in any given year understate the quantity of oil that remains. In other nations, there is no formal definition for proved reserves and their meaning is uncertain.

A casual examination of the estimates in Table 1 indicates that the size of the estimates for ultimate recoverable supply grew quickly during the first half of the twentieth century. In the 1970's there are a few large estimates, such as 5.6 trillion barrels. Since the 1980s, most estimates vary between 1.5 and 4 trillion barrels, which represents a large degree of uncertainty about the resource base.

To make the information in Table 1 usable by the algorithm that is described below, we convert estimates for ultimate recoverable supply to the quantity that remains as of January 1, 2005. To calculate the quantity of oil that remains (Q_{remain}) from estimates for ultimate recoverable supply, we subtract the quantity of crude oil produced between 1900 and 2004, 984.9 billion barrels, from the estimate for ultimate recoverable supply. To convert estimates for oil remaining to a common date, January 1, 2005, we subtract the amount of oil produced from the time the estimate was made through December 31, 2004. These conversions identify a range of values for the quantity of oil remaining, 0.8 trillion and 2.9 trillion barrels. Of these, 0.8 trillion barrels represents a conservative scenario while 2.9 trillion represents an optimistic scenario—the U.S. Department of Energy estimates that there is only a 5 percent level of probability that conventional sources of crude oil will yield 3.896 trillion barrels.

Mathematical procedure

The quantity of oil that remains corresponds to the integral of a curve that represents annual rates of production from January 1, 2005 through the exhaustion of the resource, which we assume is December 31, 2150. Production curves can follow a nearly infinite number of paths. Some paths can be eliminated based on engineering aspects of oil production. As described previously, production cannot increase continuously until the resource is exhausted, at which point production drops to zero.

We narrow the range of possible production curves based on observations from nations where much of the resource has been produced, such as the lower 48 states US, Egypt, and Norway. Their production histories show a period of increasing production, a slowing that culminates in one or more tightly spaced peaks, and then an eventual decline. Hubbert (1980) argues that this pattern can be represented most parsimoniously using a bell-shaped.

Nonetheless, there is no *a priori* reason for the production path to have a single peak or to be symmetric, and we explore both of these possibilities. There are many reasons to expect the production path to be asymmetric. The skewed distribution of the oil resource may generate a production path that falls faster than it rises. Most of the world's oil is contained in a few very large fields (Nehring, 1978). For example, there are more than 14,000 oil fields in the United States. Of these, the largest one hundred fields contain more than 30 percent of ultimate recoverable supply. Furthermore, these large fields are one or more orders of magnitude greater than the rest. This implies that production could drop sharply as giant fields are depleted and their production is replaced by lifting from much smaller fields.

Conversely, engineering and economic aspects may generate production paths that decline slower than they rise. Given the world’s dependence on conventional crude oil as a source for transportation fuels, the decline in production following a peak may generate high crude oil prices and improved technology for extracting crude oil. These changes would tend to slow the decline relative to the rise toward the peak.

To account for the uncertainty about Q_{remain} and the possibility that the production path is asymmetric, we use an iterative procedure to generate an inverted U-shaped production path with the following equations:

$$Q_t = (Q_{t-1} * (1 + R - (R/(t_{peak} - 2004) * (t - 2004)))), \text{ If } (t < t_{peak}) \qquad (1)$$

$$Q_t = (Q_{t-1} * (1 - S - (S/(t_{peak} - 2004) * (t - 2004)))), \text{ If } (t > t_{peak}) \qquad (2)$$

$$Q_{cum} = \sum_{t=2005}^{2150} Q_t \qquad (3)$$

in which Q_t is global production of conventional crude oil (million barrels) in year t, t_{peak} is the year that production peaks, R is the 2005 growth rate, S is the initial decline rate, and Q_{cum} is the quantity of oil produced between 2005 and 2150. Equation (1) is used to simulate production from 2005 through the peak in production. The declining phase of the production path is simulated using equation (2). The total quantity of oil produced from 2005 to 2150 is calculated using equation (3).

To calculate the production path that is associated with a given value of remaining oil supply (Q_{remain}), initial growth rates (R), and decline rates (S), we start with the assumption that t_{peak} occurs in 2005. These values are used in equations (1) and (2) to calculate annual oil production through 2150. Annual values are summed using equation (3) to calculate cumulative production

(Q_{cum}) and this total is compared to the value of Q_{remain}. If cumulative production is less than the estimate for the quantity that remains ($Q_{cum} < Q_{remain}$), the date of the peak is postponed by one year and the production path is recalculated. This process is repeated until cumulative production is greater than (or equal to) the estimate for the quantity that remains ($Q_{cum} \geq Q_{remain}$). At this point, the difference between cumulative production and Q_{remain} is compared to the difference generated by the production path with the peak one year earlier. The production path that generates a value for Q_{cum} that is closest to Q_{remain} is used to identify t_{peak} in for a given set of values for R, S, and Q_{remain}.

To evaluate the effect of uncertainty about the quantity of oil that remains, we simulate production paths with estimates for remaining oil supplies (Q_{remain}) that span the wide range reported in Table 1. For this analysis, the low estimate indicates another 0.8 trillion barrels to be produced as of January 1, 2005 and the high estimate indicates another 2.9 trillion barrels. Within this range, we also simulate production paths with values for Q_{remain} of 1.5 and 2.0 trillion barrels. This range embodies disparate assumptions about the geological resource base, the technologies used to recover oil, and economic/policy incentives.

To evaluate the effect of uncertainty about demand growth, oil prices, and technological development, we simulate sixteen production paths for each value of Q_{remain} using different values of R and S. We use all possible combinations of growth rates, R, and decline rates S, of .02, .04, .06, and .08. Because the growth rate varies over the production curve, we calculate the average rate of production between 2005 and t_{peak}. Beyond the peak, we calculate the average rate of growth between t_{peak} and $t_{peak + (tpeak-2005)}$. This gives some indication regarding the asymmetry in the production path, but this average does not represent the average decline rate over the waning phase of the production path.

This iterative procedure contains several advantages relative to Hubbert's original methodology. By taking historical observations as a given, the production path starts with the value of output for 2004 and eliminates the tendency for Hubbert's methodology to overstate cumulative production through 2005. The methodology also eliminates the assumption of symmetry—by allowing R and S to vary, the production path can rise and fall at different rates. Finally, it allows us to explore uncertainty about the quantity of oil that remains by using alternative values for Q_{remain} as opposed to manipulating values of Q_∞ to best fit the observed data.

IV Results

Despite large differences in Q_{remain}, R, and S, there is relatively little variation in t_{peak}. For fifty-four of the sixty-four scenarios (four values of Q_{remain} x four values of R x four values of S), t_{peak} varies between 2010 and 2032 (Table 2). As expected, there is a positive relationship between Q_{remain} and t_{peak}, but t_{peak} is relatively insensitive to large variations in Q_{remain}. That is, if we hold R and S constant, t_{peak} increases by about 20-25 years as Q_{remain} increases from 0.8 trillion barrels to 2.9 trillion barrels. For example, if 0.8 trillion barrels remain and both R and S equal .06, t_{peak} occurs in 2014 (Table 2 & Figure 2). A value of R = .06 corresponds to an average growth rate of about 3% between 2005 and 2014. If Q_{remain} is increased nearly four-fold to 2.9 trillion barrels (and R and S remain at .06), t_{peak} occurs in 2033 (Table 2 & Figure 2). Again, a value of R = .06 corresponds to an average decline rate of about 3 percent.

Similarly, changing the initial growth and decline rates has relatively little effect on t_{peak} for any given value of Q_{remain} (Figure 3). For example, t_{peak} varies between 2010 and 2017 if only 0.8 trillion barrels remain, regardless of the combination of R and S used (Table 2). If Q_{remain} is increased to 2.9 trillion barrels, t_{peak} varies between 2023-2051 (Table 2). This expansion may be somewhat misleading—postponing the peak in global production beyond 2040 is possible only of the initial growth rate R is very low (R = .02) and the decline rate is relatively fast ($R \geq$

.04). This form of asymmetry seems relatively unlikely. The most rapid increases in oil demand are occurring the in the developing nations of Asia, especially China and India. Their oil demand is likely to grow rapidly given forecasts for continued high rates of economic growth in general and oil using infrastructure, such as cars.

V Discussion

Alternative Shapes for the Production Path

We are not the first to use simple production paths to forecast t_{peak}. Wood *et al.*, (2004) identify the peak in global production from production paths that rise at a constant rate until t_{peak} and fall thereafter at constant reserves to production ratio of 10:1. Their production paths show sharp peaks that occur about 15 years later than the peak in our production paths. For example, Wood *et al.*, (2004) forecast that global oil production will peak in 2042 (Figure 1) if 3 trillion barrels ultimately are recovered (comparable to Q_{remain} = 2 trillion) and if production grows 2 percent per year prior to the peak (comparable to R = .04).

The year delay in t_{peak} is generated by the rapid decline simulated by Wood *et al* (2004)—the assumption that production falls with a constant reserve to production ratio of 10:1 causes production to decline by about 10 percent per year. But are such rapid declines rates likely? Economic considerations militate against such rapid declines. The 'pointy peak' in the production path simulated by Wood *et al.*, (2004) indicates that oil production increases by the greatest quantity the year before the peak and declines by the greatest quantity the year after the peak. These sharp changes are inconsistent with even the simplest forward-looking behavior by the oil industry. For example, the large one-year jump in production prior to t_{peak} implies large investments in the production and transportation infrastructure that are used for a single year—after the peak, increasing fractions of the infrastructure are idled by production that declines 10 percent per year. The rapid obsolescence of infrastructure is inconsistent with the effect of set-up costs on capacity investment decisions. In short, the costs of infrastructure probably cannot be justified economically by a single year of use at full capacity.

The large reduction in output after the peak also is inconsistent with the most rudimentary implementation of Hotelling's rule. A large reduction in global production, such as 10 percent, would seem to imply a significant jump in prices following the peak (especially after many decades of steadily increasing production prior to the peak). Such a price increase probably would generate an increase in rent that is larger than the real interest rate. Such a large jump would violate the optimality condition proposed by Hotelling (the present value of rents are constant over time). A large increase in real rents would give firms a strong incentive to shift some of the large production increase before the peak to after the peak (even if firms could look ahead only a couple of years). This reallocation would generate a 'smoother' peak that looks more like the production paths that are generated by our methodology.

Nor is there any *a priori* reason for the production path to have a single peak—the production path could have two or more widely spaced peaks. Simple efforts to generate paths with more than one peak indicate that the decline and rise to a secondary peak consume large amounts of Q_{remain} such that the second peak is either (1) lower than the peak that would have been achieved if production had continued to rise beyond the 'first' peak and/or (2) the decline after the second peak is very fast. In summary, it is not possible to draw a reasonable production path for a given value of Q_{remain} that peaks later and at a greater annual rate of production relative to paths that have a single peak.

Will the Market Supply Alternative Fuels in a Timely Fashion?

If the window for the global peak in oil production identified by the simple methodology is accurate, global production of conventional crude oil may start to decline sometimes between 2010 and 2031. As production declines, shortfalls will be eliminated by a combination of three options: (1) increasing the production of alternative fuels, (2) increasing the efficiency of the oil using capital stock, and (3) reducing economic activity. Of these three, reducing economic activity reduces total social welfare and is not considered further.

Increasing the efficiency of energy using capital is desirable for many reasons, but the putty-clay model of oil-using capital implies that this option is relatively limited. The putty-clay model hypothesizes that there is a large variation in the efficiency of oil-using capital available for purchase, but once installed, there is relatively little room for efficiency gains other than fuel switching. This rigidity, along with the long life of oil-using capital implies that it will be relatively difficult to reduce oil use by the existing capital stock after the global production of conventional crude oil peaks (we assume that the globe is not building inventories around t_{peak} therefore, oil production is consistent with oil demand by the full utilization of oil-burning capital stock that exists at t_{peak}).

Instead, declining production will be most easily offset by replacing conventional crude oil with alternatives. We make no arguments about what type(s) of fuels will replace conventional crude oil. Rather we assess the rate at which these alternatives will be needed and whether the market will provide them in a timely fashion.

We can approximate the rate at which alternatives to conventional crude oil are needed based on the rate at which production declines. If we assume that the sum of demand for conventional crude oil and potential replacements stops growing when production peaks (this is a very conservative assumption—it implicitly assumes that net additions to capital stock use no conventional crude oil or potential replacements for conventional crude oil), we can approximate the demand for alternative fuels by the difference between the production of conventional crude oil in t_{peak} and subsequent rates of production (Figure 2(b)). The implied demand for alternative fuels reaches nearly 10 mbd, which is the current rate of production by Saudi Arabia, for most values of Q_{remain}, R, and S within five to ten years of the peak. Demand for alternatives rises even faster in scenarios that postpone t_{peak} by allowing production to decline faster than it rose, especially the production paths simulated by Wood *et al*., (2004). For example, for the 'pointy' production path in figure 1, the demand for alternatives rises to 10 mbd in less than two years, and to slightly more than 27mbd in five years.

Increasing demand for alternatives raises an important question. Will the market ensure the investment that is needed to add the equivalent of a new Saudi Arabia within a decade of t_{peak}? The capital intensity of oil production implies considerable foresight will be needed to generate the required infrastructure in a timely fashion. What signals could generate such foresight? A steady rise in oil prices prior to t_{peak} would encourage investments in alternative fuels, but such a rise leading to t_{peak} is unlikely. As described previously, most oil is found in a few very large fields therefore, extraction costs may not increase significantly until these fields are depleted and replaced with smaller fields further from the surface in more remote areas. The discontinuous change in extraction costs is illustrated by the production history in the lower 48 states of the US, where the real cost of producing oil remained steady or declined between 1936 and the late 1970's even as production tripled, but then real costs increased more than four fold within a decade as production declined after the peak (Kaufmann and Cleveland, 2001).

Alternatively, prices may rise significantly before t_{peak} for economic or political reasons not related to depletion. For example, OPEC producers may be able to increase revenues if they slow the rate at which they add to operable capacity (Gately, 1995; Dées *et al*., in press). But the implicit lack of permanence associated with a rise may not be sufficient to encourage the production of alternatives. If prices rise ahead of extraction costs, OPEC producers retain the ability to reduce prices by opening additional capacity. The subsequent drop in prices could diminish the economic viability of alternative fuels. The potential for increased production and lower prices, as happened in 1986, may discourage investment in alternatives.

Without a cost-induced price signal, investments in alternative sources of energy may be generated by the anticipated decline in production after t_{peak}. Anticipating t_{peak} is critical because the capital infrastructure that is needed to produce significant quantities of alternatives will require long lead times. For example, the United States Geological Survey (1998) forecasts that ten years are needed to produce 1mbd from the Artic National Wildlife refuge using a known technology for conventional crude oil. The infrastructure required to produce alternatives is likely to be more expensive, require longer lead times, and involve more financial risk (Hirsh *et al.,* 2005).

Long lead times and uncertainty about t_{peak} generate an externality that causes an asymmetry in the investment schedule that maximizes welfare for firms and society. Without uncertainty, firms invest in energy producing infrastructure that will supply alternatives starting at t_{peak}. This optimal investment path generates alternative sources of energy that maximize profits for firms and total social welfare(Figure 4).

Uncertainty about t_{peak} creates a risk to firms and society that the optimal investment path will generate alternatives before or after t_{peak}. These two possibilities create asymmetric outcomes for firms and society in which society prefers an investment schedule that generates alternative fuels prior to the expected date for t_{peak} while energy-producing firms will prefer an investment schedule that generates alternative fuels after the expected date for t_{peak} (Figure 3).

To explain this asymmetry, suppose t_{peak} occurs later than expected such that alternative fuels are produced prior to t_{peak}. In this case, investment in alternative fuels occurred too soon, which increases the present value of their cost to society and to firms, which reduces total social welfare and profits. Profits for the producers of alternative fuels may be reduced further if the continued availability of conventional crude oil before t_{peak} keeps alternative fuels from the market or forces firms to sell alternative fuels at a discount relative to the price anticipated following the peak. Nonetheless, this investment path ensures that sufficient supplies of alternative fuels are available to society when production peaks.

Conversely, sufficient supplies of alternative fuels are not available if t_{peak} occurs sooner than expected. This outcome has little effect on the present value of rents for private firms that produce alternatives. But the combination of declining crude oil production, a lack of alternative fuels, and the resultant increase in price implies a large oil shock that can cause a significant decline in total social welfare (Hamilton, 2003).

VI Conclusion

Although there is considerable uncertainty about the quantity of oil that remains, the rate at which oil demand will grow prior to the peak, and the rate at which production will decline after the peak, these uncertainties have relatively little effect on the date at which global oil production peaks. Under most assumptions, global production of conventional crude oil will decline sometime between 2010 and 2032. Although these dates seem far away, society is rapidly approach the date at which decisions are needed to generate an investment schedule consistent with the long lead times that are required to generate the capital infrastructure needed to produce and consume significant quantities of alternatives to conventional crude oil. Furthermore, there is reason to believe that the market will not generate this infrastructure in a timely fashion. Uncertainty about the date of the peak in global oil production creates an asymmetry in which society prefers an investment schedule that generates alternative fuels prior to the expected date for t_{peak} while energy-producing firms prefer an investment schedule that generates alternative fuels after the expected date for t_{peak}. To avoid large reductions in total social welfare that are implied by this asymmetry, some government intervention may be needed to alter the investment schedule that optimizes firm profits when the date of t_{peak} is uncertain.

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Table 2 The effect of uncertainty about growth rates, decline rates and remaining oil supply on the date at which global oil production peaks.

		Decline Rate (R)			
Increase Rate (G)	Q_{remain}	.02	.04	.06	.08
.02	0.8	2011	2014	2015	2017
	1.5	2020	2025	2027	2029
	2.0	2026	2032	2035	2038
	2.9	2039	2045	2049	2051
.04	0.8	2010	2013	2014	2015
	1.5	2018	2022	2024	2025
	2.0	2023	2027	2029	2031
	2.9	2031	2036	2039	2040
.06	0.8	2010	2012	2014	2014
	1.5	2016	2019	2021	2023
	2.0	2020	2024	2026	2027
	2.9	2026	2032	2033	2035
.08	0.8	2010	2012	2013	2014
	1.5	2015	2018	2020	2021
	2.0	2018	2022	2023	2024
	2.9	2023	2027	2029	2031

Figure Caption

Figure 1 The observed rate of oil production (black line). A Hubbert curve fit to these data with a Q_∞ of 1.8 trillion barrels (red line) peak in 1998—the peak is in 2006 if Q_∞ equals 3 trillion barrels (pink line). If another 2 trillion barrels remain, and if R and S equal 0.04, production peaks in 2026. If another 2 trillion barrels remain and production rises at 2 percent annually until reserves drop to a reserves to production ratio of 10:1, global production peaks in 2042. If production continues to rise until the 2 trillion barrels are depleted, global production peaks in 2050.

Figure 2. (a) The peak in global oil production is delayed from 2014 to 2021, to 2026, and 2033 as the value of Q_{remain} is increased from 0.8 trillion barrels (red line), to 1.5 trillion barrels (blue line), to 2 trillion barrels (green line), to 2.9 trillion barrels (pink line) for values of R and S of

0.06.). **(b)** the demand for alternatives to crude oil following the peak in production from figure 2 (a) if 0.8 trillion barrels remain (red line), if 1.5 trillion barrels remain (blue line), if 2 trillion barrels remain (green line), if 2.9 trillion barrels remain (pink line), if the demand for fuels derived from crude oil stops growing at the date of the peak.

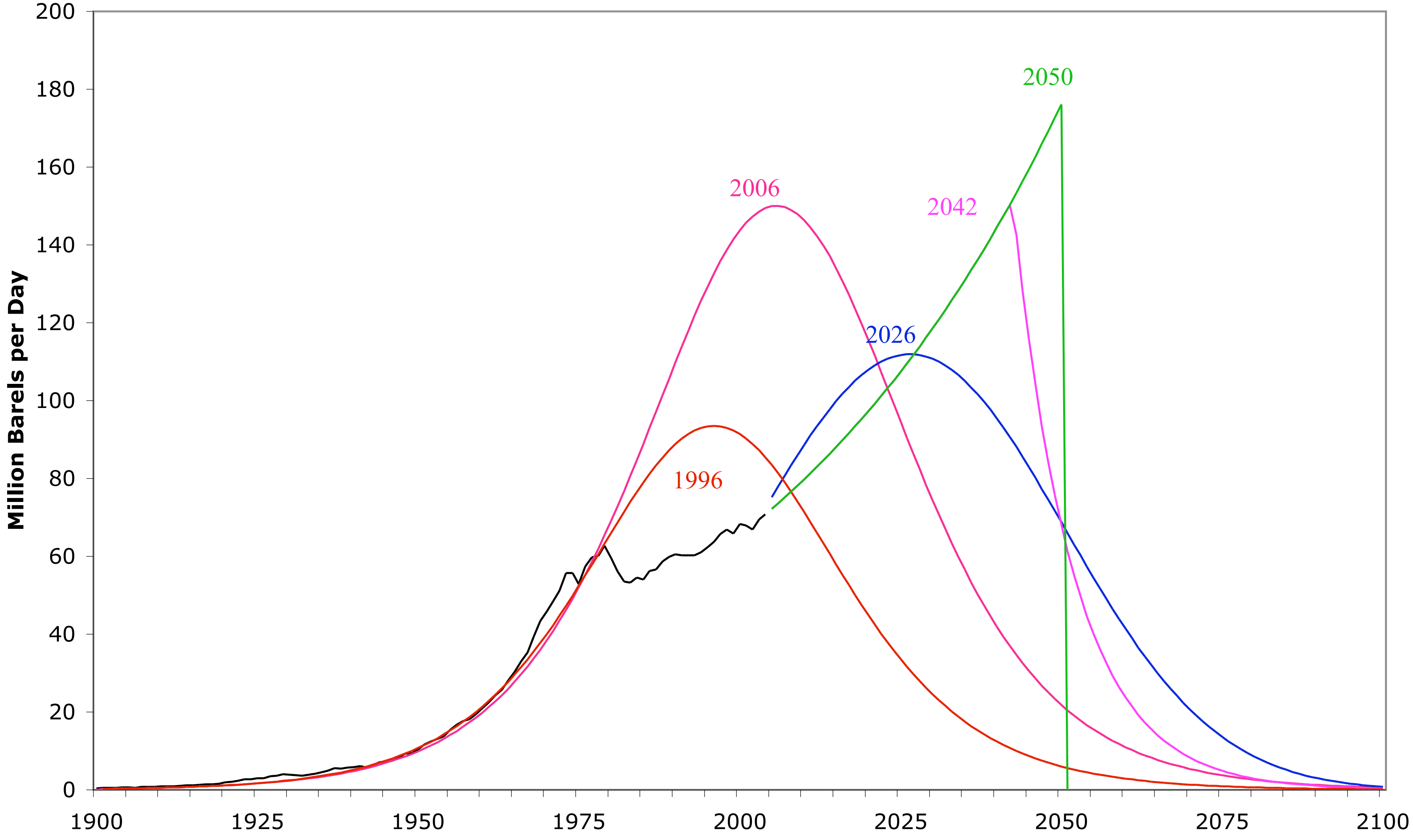
Figure 3 The peak in global oil production for a value of Q_{remain}= 2 trillion barrels shifts from 2018 (green line; R= 0.08, S= 0.02), to 2024 (red line; R = 0.08, S = 0.08)., 2026 (blue line; R = 0.02, S = 0.02), 2038 (R = 0.02, S = 0.08).

Figure 4 Investment schedule that maximizes the present value of social welfare if the observed peak in global oil production occurs in t_{peak} is given in black. The five-year investments needed to make alternatives available at the peak are given in rectangles B and C. If the observed peak occurs after the anticipated peak, investment is too soon (blue line), as given by rectangle A. If the observed peak occurs before the anticipated peak, the loss in total social welfare associated with the delayed production of alternative fuels (red line) is given by rectangle (D).

Table 1

Source	Year of Estimate	Estimator	Ultimate Estimates (Million Barrels of Oil)	Oil Remaining Estimates	Oil left (as of 2005 in millions of barrels)		
					Low Range	Middle Range	High Range
Porter, American Petroleum Institute (1995)	1919	White	43,000			-941,882	
Porter, American Petroleum Institute (1995)	1942	Pratt et al.	600,000			-384,882	
Porter, American Petroleum Institute (1995)	1946	Duce	400,000			-584,882	
Porter, American Petroleum Institute (1995)	1946	Pogue	555,000			-429,882	
Porter, American Petroleum Institute (1995)	1948	Weeks	610,000			-374,882	
Porter, American Petroleum Institute (1995)	1949	Levorsen	1,500,000			515,118	
Porter, American Petroleum Institute (1995)	1949	Weeks	1,010,000			25,118	
Porter, American Petroleum Institute (1995)	1953	Macnaughton	1,000,000			15,118	
Porter, American Petroleum Institute (1995)	1956	Hubbert	1,250,000			265,118	
Porter, American Petroleum Institute (1995)	1956	Weeks	1,178,000			193,118	
Hall, Cleveland, Kaufmann (1986)	1958	Weeks	1,500,000- 3,000,000		515,118		2,015,118
Hall, Cleveland, Kaufmann (1986)	1959	Weeks	2,000,000- 3,500,000		1,015,118		2,515,118
Hall, Cleveland, Kaufmann (1986)	1965	Hendricks	1,984,000- 2,480,000		999,118		1,495,118
Porter, American Petroleum Institute (1995)	1967	Ryman	2,090,000			1,105,118	
Porter, American Petroleum Institute (1995)	1968	Shell	1,800,000			815,118	
Hall, Cleveland, Kaufmann (1986)	1968	Weeks	2,200,000- 3,350,000		1,215,118		2,365,118
Hall, Cleveland, Kaufmann (1986)	1969	Hubbert	1,350,000- 2,000,000		365,118		1,015,118
Hall, Cleveland, Kaufmann (1986)	1970	Moody	1,800,000			815,118	
Hall, Cleveland, Kaufmann (1986)	1971	Warman	1,200,000- 2,000,000		215,118		1,015,118
Porter, American Petroleum Institute (1995)	1971	Weeks	2,290,000			1,305,118	
Hall, Cleveland, Kaufmann (1986)	1972	Jodry	1,952,000			967,118	
Porter, American Petroleum Institute (1995)	1973	Moody, Esser	2,297,000			1,312,118	
Hall, Cleveland, Kaufmann (1986)	1973	Odell	4,000,000			3,015,118	
Hall, Cleveland, Kaufmann (1986)	1974	Kirkby, Adams	1,600,000- 2,000,000		615,118		1,015,118
Porter, American Petroleum Institute (1995)	1975	Halbouty	2,128,000			1,143,118	
Hall, Cleveland, Kaufmann (1986)	1975	Moody, Esser	1,312,000-2,000,000- 3,237,000		327,118	1,015,118	2,252,118
Hall, Cleveland, Kaufmann (1986)	1975	Moody	1,705,000- 2,030,000- 2,505,000		720,118	1,045,118	1,520,118
Hall, Cleveland, Kaufmann (1986)	1976	Grossling	1,960,000- 5,600,000 (method 1)		975,118		4,615,118
Hall, Cleveland, Kaufmann (1986)	1976	Grossling	2,200,000- 3,000,000 (method 2)		1,215,118		2,015,118
Hall, Cleveland, Kaufmann (1986)	1976	Klemme	1,600,000			615,118	
Hall, Cleveland, Kaufmann (1986)	1977	Parent, Linden	2,130,000- 2,480,000		1,145,118		1,495,118
Hall, Cleveland, Kaufmann (1986)	1977	Delphi	1,799,000 (middle group mean)			814,118	
Hall, Cleveland, Kaufmann (1986)	1978	Nehring	1,700,000- 2,300,000		715,118		1,315,118
Hall, Cleveland, Kaufmann (1986)	1979	Halbouty, Moody	1,421,000- 2,128,000- 3,556,000		436,118	1,143,118	2,571,118
Hall, Cleveland, Kaufmann (1986)	1979	Nehring	1,600,000- 2,000,000		615,118		1,015,118
Porter, American Petroleum Institute (1995)	1980	Masters et al.	1,222,000- 2,593,000		237,118		1,608,118
Masters, World Petroleum Congress (1983)	1983	Masters, Root, Dietzman	1,722,000			737,118	
Porter, American Petroleum Institute (1995)	1984	Masters et al.	1,600,000- 2,200,000		615,118		1,215,118
Riva, Congression Research Service (1987)	1986	Riva, Jr.		1,200,000		781,487	
Porter, American Petroleum Institute (1995)	1989	Masters et al.	2,000,000- 2,700,000		1,015,118		1,715,118
Masters, World Petroleum Congress (1991)	1991	Masters, Root, Attanasi	2,171,000			1,186,118	
Masters, Root, Attanasi (1991)	1991	Masters, Root, Attanasi	2,079,000			1,094,118	
Porter, American Petroleum Institute (1995)	1992	Masters et al.	2,100,000- 2,800,000		1,115,118		1,815,118
Porter, American Petroleum Institute (1995)	1993	Masters et al.	2,400,000			1,415,118	
Porter, American Petroleum Institute (1995)	1994	Campbell	1,700,000			715,118	
Laherrere (2001)	1998	Perrodon et al.	1,700,000- 1,800,000- 2,200,000		715,118	815,118	1,215,118
Campbell, Laherrere (1998)	1998	Campbell, Laherrere		1,000,000		825,753	
Explorer (2000)	2000	Ahlbrandt		2,120,000		1,994,214	
U.S Geological Survey (2000)	2000	Petroconsultants, NRG	2,659,000			1,674,118	
Ruppert (2002)	2002	Campbell		1,000,000		923,930	
Energy Information Administration (2004)	2004	USGS	2,248,000- 3,003,000 (mean)- 3,896,000		1,263,118	2,018,118	2,911,118

Figure 1


Million Barels per Day
200
180
160
140
120
100
80
60
40
20
0
1900
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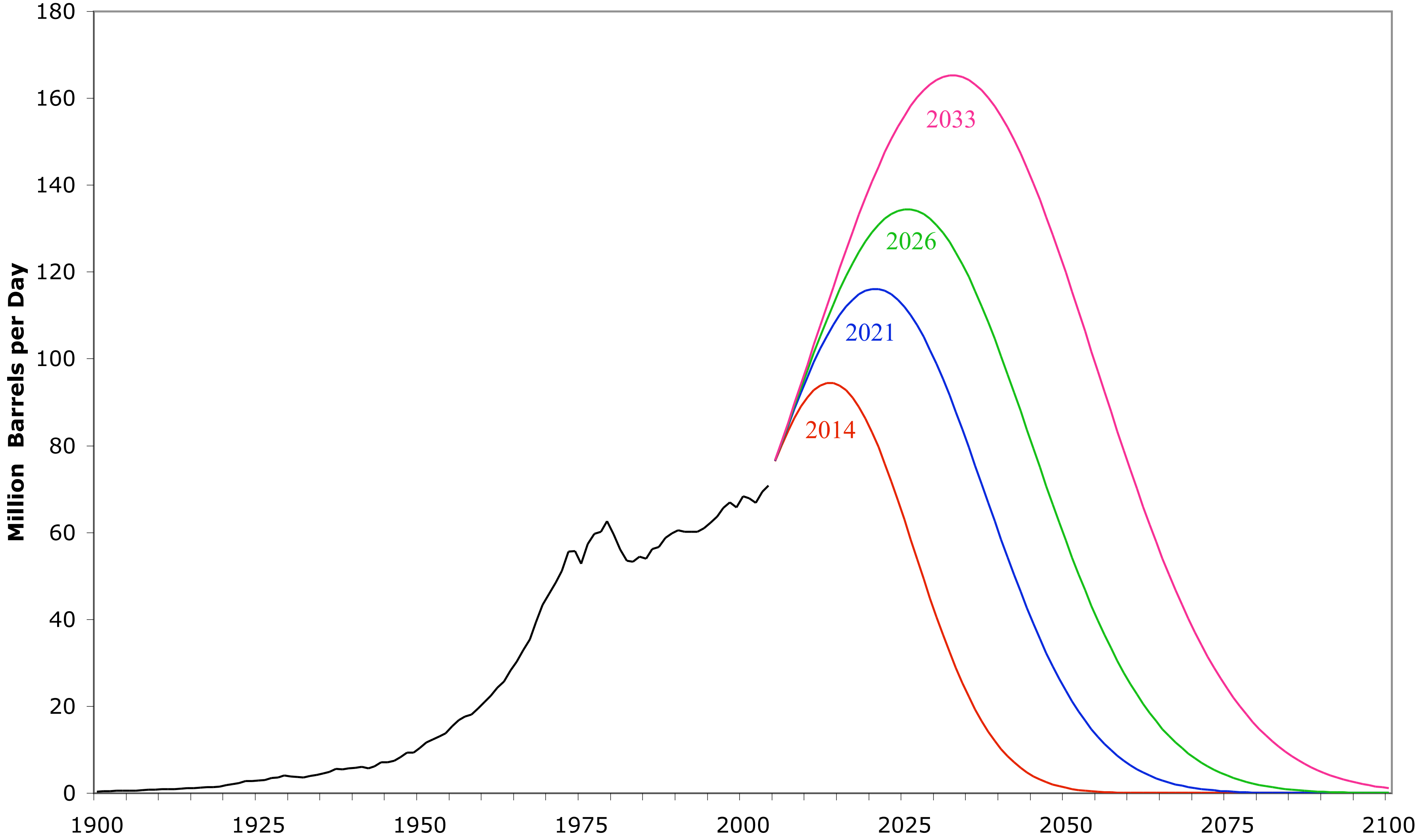
1950
1975
2000
2025
2050
2075
2100
2050
2006
2042
2026
1996

Figure 2(a)


Million Barrels per Day
180
160
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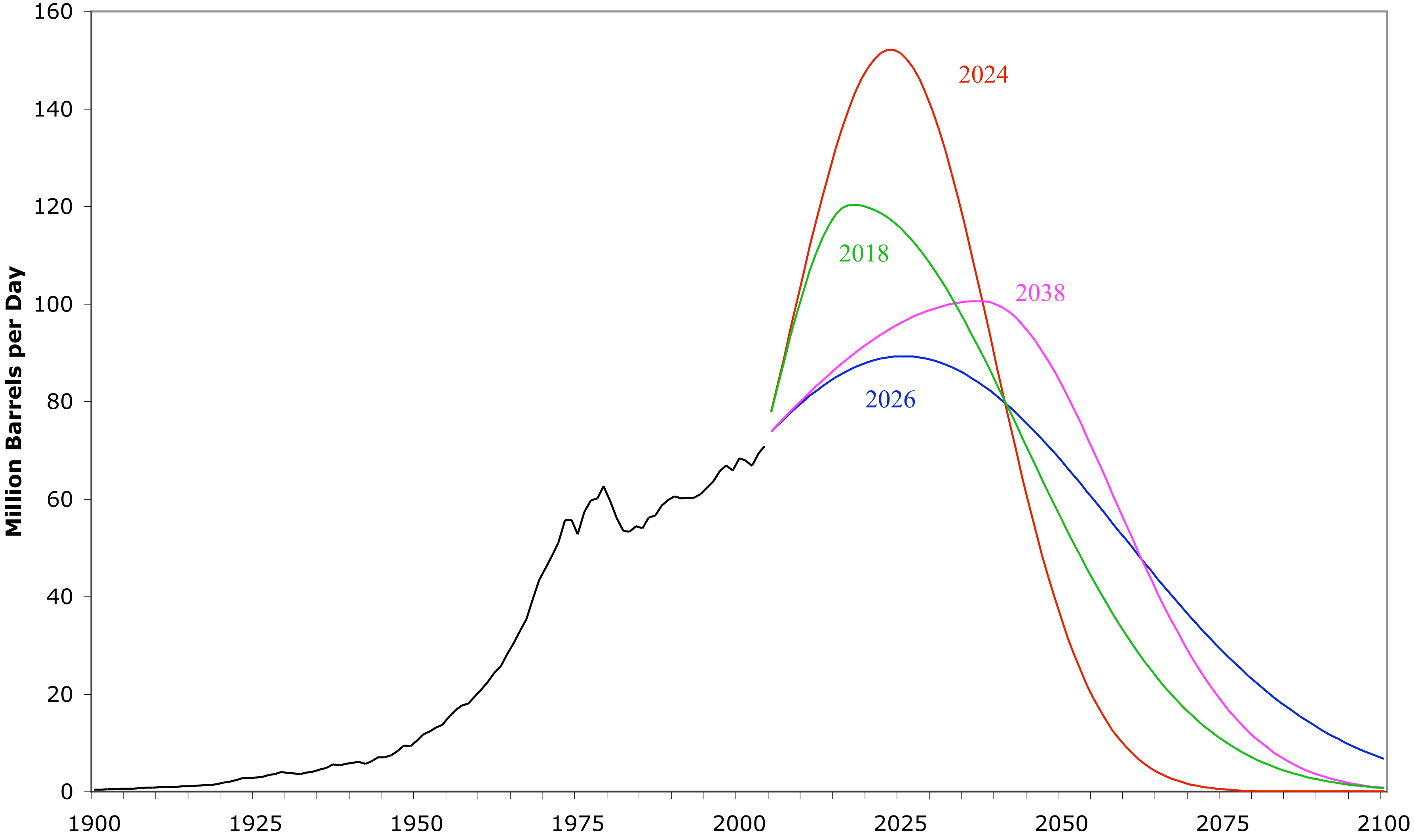
2014

Figure 3


160
140
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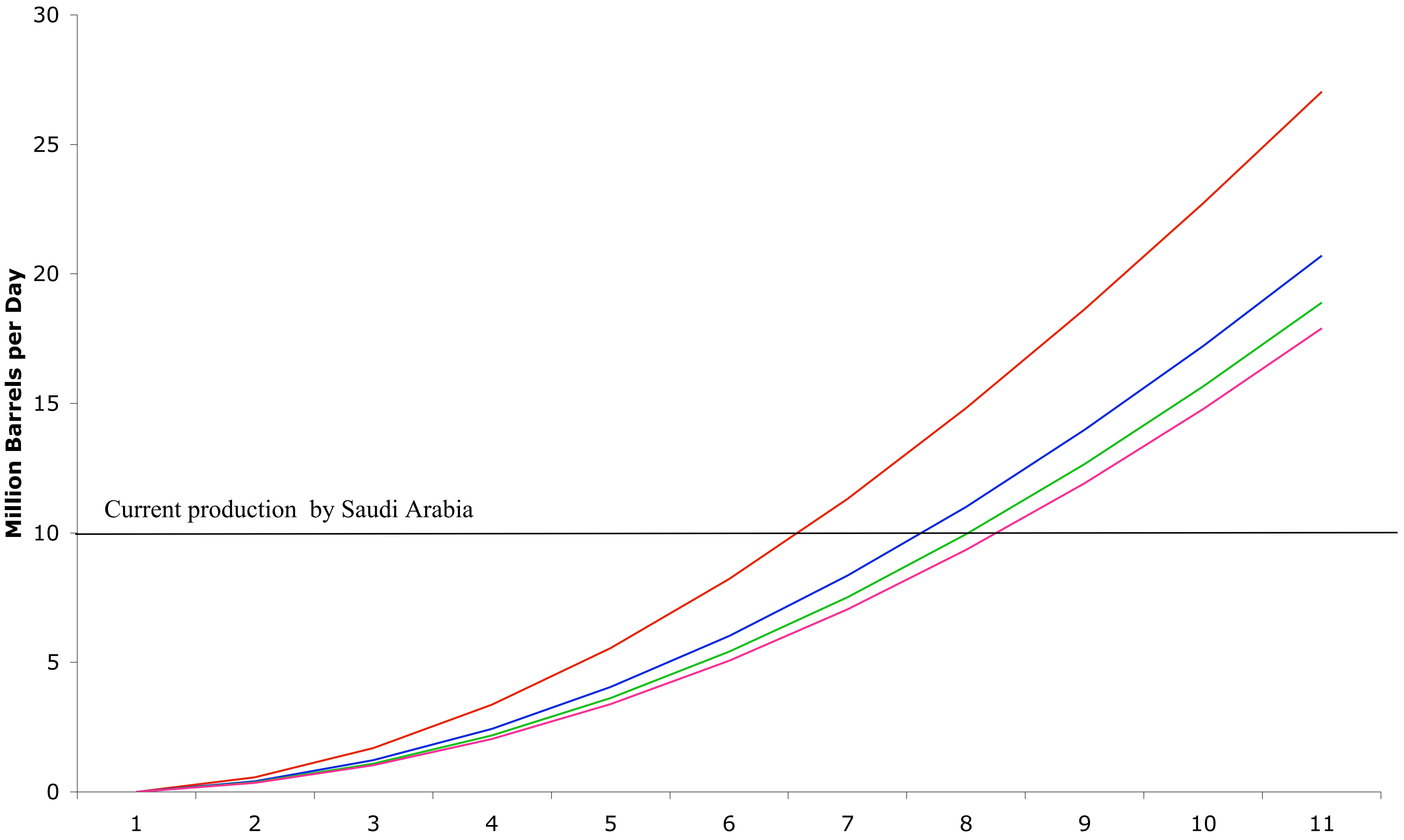
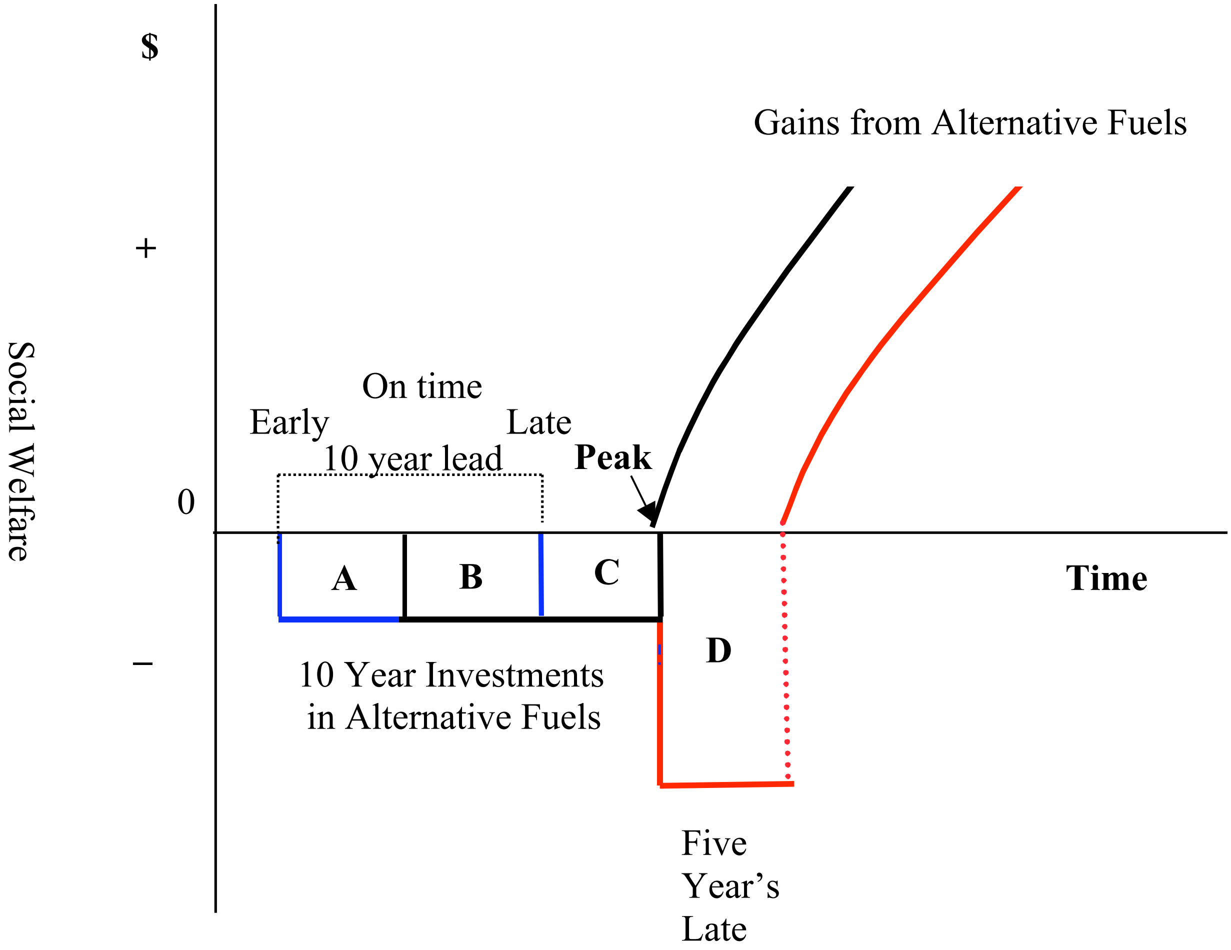
Million Barrels per Day
1900
1925
1950
1975
2000
2025
2050
2075
2100
2024
2018
2038
2026

Figure 2(b)



Million Barrels per Day
30
25
20
15
10
5
0
1
2
3
4
5
6
7
8
9
10
11
Current production by Saudi Arabia

Figure 4


$
+
Social Welfare
0
–
Gains from Alternative Fuels
On time
Early
Late
10 year lead
Peak
A
B
C
D
Time
10 Year Investments
in Alternative Fuels
Five
Year's
Late