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Energy return on investment, peak oil, and the end of economic growth

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Economic growth over the past 40 years has used increasing quantities of fossil energy, and most importantly oil. Yet, our ability to increase the global supply of conventional crude oil much beyond current levels is doubtful, which may pose a problem for continued economic growth. Our research indicates that, due to the depletion of conventional, and hence cheap, crude oil supplies (i.e., peak oil), increasing the supply of oil in the future would require exploiting lower quality resources (i.e., expensive), and thus could occur only at high prices. This situation creates a system of feedbacks that can be aptly described as an economic growth paradox: increasing the oil supply to support economic growth will require high oil prices that will undermine that economic growth. From this we conclude that the economic growth of the past 40 years is unlikely to continue in the long term unless there is some remarkable change in how we manage our economy.

Introduction

Historically, economic growth has been highly correlated with increases in oil consumption, and, aside from a few short supply interruptions, oil supplies have kept pace with growing demand. As a result, real gross domestic product (GDP) tripled in value while oil consumption grew by 40% from 1970 through 2008. Unfortunately, the oil world of today is much different from the oil world over the past 40 years. Numerous analyses offer evidence that we consider quite convincing that global society is entering the era of peak oil,[a] that is, the era in which conventional oil supply is unable to increase significantly and will eventually begin to decline.[1–3]

Oil, more than any other energy source, is vital to economies because of its ubiquitous application as fuels and feedstocks in manufacturing and industrial production, as well as in transportation.

Since 1970, spikes in the price of oil have been a root cause of most recessions. For example, in 1973, precipitated by the Arab Oil Embargo, the price of oil jumped from $3 to $12 a barrel (bbl) in a matter of months, creating the largest recession thereto since the Great Depression. The price spike had at least four immediate effects within the economy: (1) oil consumption declined, (2) a large proportion of capital stocks and existing technology became too expensive to use, (3) the marginal cost of production increased for nearly every manufactured good, and (4) the cost of transportation fuels increased.[4] On the other hand, expansionary periods tend to be associated with the opposite oil signature: prolonged periods of relatively low oil prices that increase aggregate demand and lower marginal production costs, all leading to, or at least associated with, economic growth.

Numerous theories attempting to explain business cycles have been posited over the past century, each offering a unique explanation for the causes of—and solutions to—recessions, including Keynesian theory, the Monetarist model, the Rational

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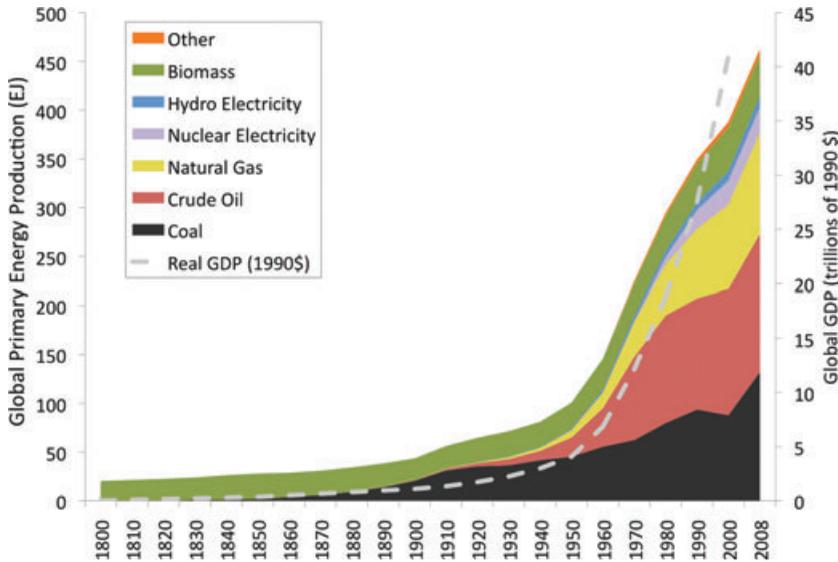[a] Period in which global oil production reaches a maximum.

Figure 1. Energy production and GDP for the world from 1830 to 2000. Data from Kremmer and Smil.[5,6] (In color in *Annals* online.)

Expectations model, Real Business Cycle models, New (Neo-) Keynesian models, etc.[4] Yet, for all the differences among these theories, they all share one implicit assumption: a return to a growing economy, that is, growing GDP, is in fact possible. Historically, there has been no reason to question this assumption, as GDP, incomes, and most other measures of economic growth have in fact grown steadily over the past century. But if we are entering an era of peak oil, then for the first time in history we may be asked to grow the economy while simultaneously decreasing oil consumption, something that has yet to occur within the United States since the discovery of oil.

Objectives

The primary objectives of this review are to examine (1) the degree to which abundant and inexpensive oil is integral to economic growth, and how the future supply of that oil is in jeopardy; (2) the discourse on peak oil and provide what we believe is both novel and compelling evidence indicating that society is indeed in the era of peak oil; (3) the discourse on net energy[b] and discuss how searching for new sources of oil may decrease the amount of net energy provided to society and also exacerbate the effects of oil depletion on the economy; and (4) how

[b] Energy remaining from a process after accounting for the energy used in that process.

peak oil and net energy indicate that increasing oil supply will require high oil prices in the future.

Economic growth and business cycles from an energy perspective

Economic growth, from an energy perspective, has many of the same characteristics as the fundamental growth process that every living creature, species, and population on earth undertakes during their lifetime. Energy is captured by a system (the economy or a creature) and allocated first to the maintenance (metabolism) of the system and then, if there is energy remaining, to growth and/or reproduction. For example, each of us must ingest enough food during the growth phases of life to pay not only for our metabolism but also to convert some of the additional food into bone, connective tissue, etc., which is used to grow the body or create offspring. Likewise, the economy must acquire enough energy to pay not only for its metabolism, for example, fighting depreciation of existing capital, but also to pay for the construction of replacement or, sometimes, new capital. The important point here is that the construction of new capital, that is, economic growth, requires the input of "net" energy, which is the energy beyond that required for metabolic purposes.

By extension, for the economy to grow over time there must be an increase in the flow of net energy
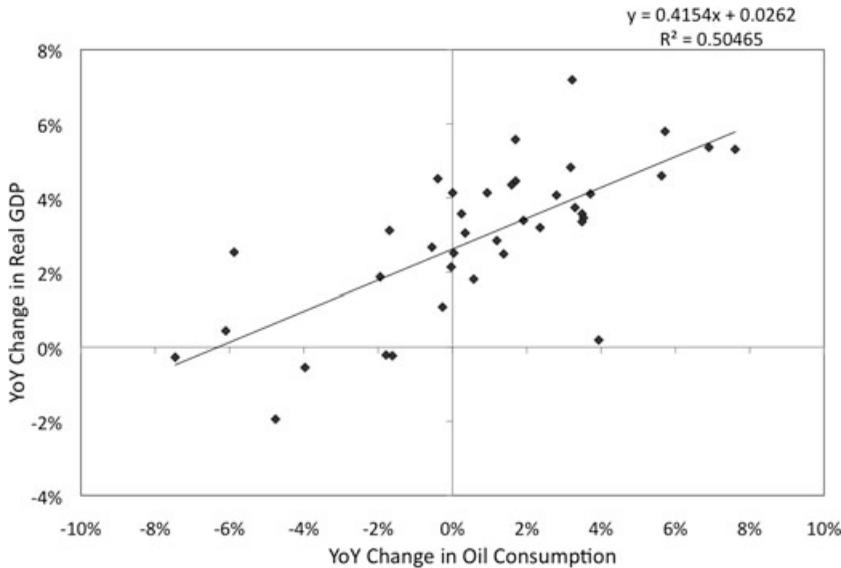
$$y = 0.4154x + 0.0262$$
$$R^2 = 0.50465$$

Figure 2. Correlation of YoY changes in oil consumption with YoY changes in the real GDP, for the United States from 1970 through 2008. Oil consumption data from the BP Statistical Review of 2009 and real GDP data from the St. Louis Federal Reserve.[7,8]

and materials through the economy. Quite simply, economic production is a work process, and work requires energy. This logic is an extension of the laws of thermodynamics, which state that (1) energy cannot be created nor destroyed, and (2) energy is degraded during any work process so that the initial inventory can do less work. As Daly and Farley describe, the first law places a theoretical limit on the supply of goods and services that the economy can provide, and the second law sets a limit on the practical availability of matter and energy.[5] In other words, the laws of thermodynamics state that to produce goods and services, energy must be used, and once this energy is used it is degraded to a point where it can no longer be reused to power the same process again. Thus to increase production over time, that is, to grow the economy, we must either increase the energy supply or increase the efficiency with which we use our source energy.

This energy-based theory of economic growth is supported by data: the consumption of every major energy source has increased with GDP since the mid-1800s (Fig. 1). Throughout this growth period, however, there have been numerous oscillations between periods of growth and recessions. Recessions are defined by the Bureau of Economic Research as "a significant decline in economic activity spread across the economy, lasting more than a few months, normally visible in real GDP, real income, employ-

ment, industrial production, and wholesale-retail sales."[10] From 1970 until 2007, there have been five recessions within the United States, and examining these recessions from an energy perspective elucidates a common mechanism underlying recent business cycles: oil consumption tends to be higher during expansions and lower during recessions, and prices tend to be lower during expansions and higher during recessions.

Plotting the year-on-year (YoY) growth rates of oil consumption and real GDP provides a more explicit analysis of the relation between economic growth and oil consumption (Fig. 2). About half of the variation in economic growth, that is, recessionary versus expansionary periods, can be explained by the variation in oil consumption alone. But correlation is not causation, and the important question is whether increasing oil consumption causes economic growth, or conversely, whether economic growth causes increases in oil consumption.

There are a myriad of publications on the topic of whether or not energy consumption causes economic growth.[11] Unfortunately, the literature is confounding, due mainly to two issues: energy quality and substitution effects. Energy quality refers to many things, but in the economic sense energy quality pertains mainly to the utility of a fuel, which is a combination of its transportability, storability, energy density, etc. Consequently, the utility of a fuel

is reflected in its price, which is why the price per energy unit of coal is much lower than the price per energy unit of electricity, that is, electricity is deemed to have a higher quality. Yet despite this difference in quality, most energy-economic analyses assume that a BTU of coal has the same economic utility as a BTU of electricity. Consequently, the substitution of high-quality energy sources, such as electricity, for low-quality energy sources, such as coal, is often missed.[12]

Cleveland *et al.* analyzed the impact of these two factors on the causal relation between energy consumption and economic growth.[12] Their results indicated that increases in energy consumption caused economic growth when they adjusted the data for quality and accounted for substitution. Other subsequent analyses that adjusted for energy quality support the result that energy consumption causes economic growth.[13] It is important to observe that the notion of causality used in this sense is not the same as generic causality, and hence it should be interpreted differently. The statistical causality used in these studies means more that "energy is a limiting factor in economic growth" (p. 281).[13,14]

In sum, our analysis indicates that about 50% of the changes in economic growth over the past 40 years are explained by the changes in oil consumption alone. In addition, the work by Cleveland *et al.*[12] indicates that changes in oil consumption cause changes in economic growth, or that economic growth is bound by the energy available. These two points support the idea that energy consumption, and oil consumption in particular, is of the utmost importance for economic growth.

Yet, oil consumption is rarely used by neoclassical economists as a means of explaining economic growth. For example, Knoop describes the 1973 recession in terms of high oil prices, high unemployment, and inflation, yet omits mentioning that oil consumption declined 4% during the first year and 2% during the second year.[4] Later in the same description, Knoop[4] claims that the emergence from this recession in 1975 was due to a decrease in both the price of oil and inflation, and an increase in money supply. To be sure, these factors contributed to the economic expansion in 1975, but what is omitted, again, is the simple fact that lower oil prices led to increased oil consumption enabling greater economic output.

Thus, we present the hypothesis that higher oil prices and lower oil consumption are indicative of recessions. Likewise, economic growth requires maintaining lower oil prices while simultaneously increasing oil supply. The data support these hypotheses: the inflation-adjusted price of oil averaged across all expansionary years from 1970 to 2008 was $37/bbl compared to $58/bbl averaged across recessionary years, whereas oil consumption grew by 2% on average per year during expansionary years compared to decreasing by 3% per year during recessionary years (Table 1, Figs. 3 and 4).

Although this analysis of recessions and expansions may seem like simple economics, that is, high prices lead to low demand and low prices lead to high demand, the exact mechanism connecting energy, economic growth, and business cycles is a bit more complicated. Hall *et al.* and Murphy and Hall state that when energy prices increase, expenditures are reallocated from areas that had previously added to GDP, mainly discretionary consumption, toward paying for more expensive energy.[15,16] In this way, higher energy prices lead to recessions by diverting money from the economy toward energy only. The data show that major recessions seem to occur when energy expenditures as a percentage of GDP climb above a threshold of roughly 5.5% (Fig. 5). It is worth noting, however, that this relation did not hold for the smaller recessions of the early 1990s and 2000s. This is probably a result of the fact that the cost of oil is only one of the many possible causes of—and solutions to—recessions.

The following two questions become particularly germane: What are the implications for economic growth if (1) oil supplies are unable to increase with demand, or (2) oil supplies increase but at an increased price? To undertake this inquiry, we must examine first the current and future status of oil supply; then, we can make inferences about what the future of oil supply and price may mean for economic growth. The subsequent section discusses the future of oil supplies, specifically how both depletion and high-cost oil can or are likely to impact economic growth.

Peak oil and net energy

Each recession and expansionary period has had the same energy signature: low oil consumption and high oil price during recessions and high oil consumption and low oil price during expansions

Table 1. Breakdown of recessions and expansionary years from 1973 through 2008, including the YoY change in oil price, oil consumption, and real GDP

		YoY change in		
		Oil price	Oil consumption	Real GDP
Recessions				
The Arab Oil Embargo,	1973	25%	6%	6%
November 1973–March 1975	1974	217%	−4%	−1%
	1975	−9%	−2%	0%
The Iranian Revolution, January	1980	3%	−7%	0%
1980–November 1982	1981	−12%	−6%	3%
	1982	−14%	−5%	−2%
Early 1990s, July 1990–March 1991	1990	24%	−2%	2%
	1991	−19%	−2%	0%
Dot-com and September 11th, March	2001	−17%	0%	1%
2001–November 2001				
Current recession, December	2007	8%	0%	2%
2007–N/A	2008	29%	−6%	0%
Average across all recessions		21%	−3%	1%
Expansions				
1976–1979	1976	5%	7%	5%
	1977	2%	6%	5%
	1978	−6%	2%	6%
	1979	103%	−2%	3%
1983–1989	1983	−13%	0%	5%
	1984	−9%	3%	7%
	1985	−5%	0%	4%
	1986	−49%	4%	3%
	1987	24%	2%	3%
	1988	−22%	4%	4%
	1989	16%	0%	4%
1992–2000	1992	−6%	2%	3%
	1993	−14%	1%	3%
	1994	−9%	3%	4%
	1995	5%	0%	3%
	1996	18%	3%	4%
	1997	−9%	2%	4%
	1998	−33%	2%	4%
	1999	36%	3%	5%
	2000	54%	1%	4%
2002–2007	2002	0%	1%	2%
	2003	12%	1%	2%
	2004	29%	3%	4%
	2005	38%	0%	3%
	2006	16%	−1%	3%
	2007	8%	0%	2%
Average across all expansions		7%	2%	4%

Sources: Energy data are from the EIA.[7] GDP data are from the St. Louis Federal Exchange.[7] Data on recessions are from the BEA.[18]
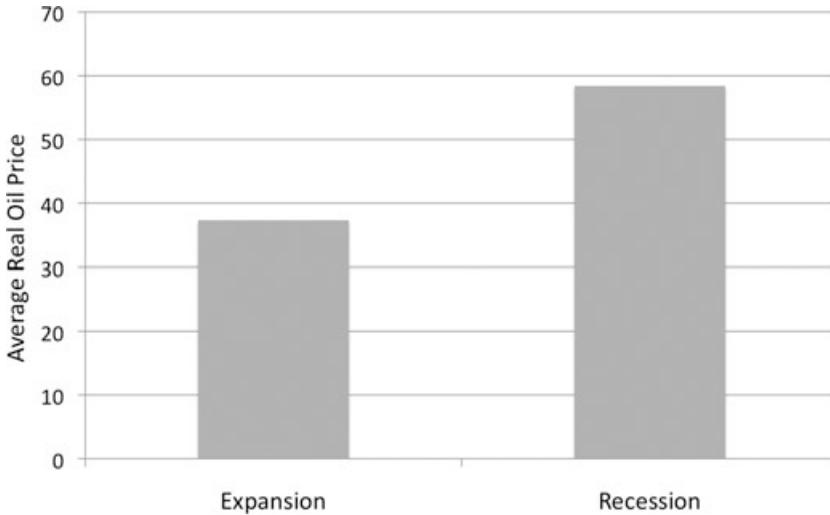
Figure 3. Real oil prices averaged over expansionary and recessionary periods from 1970 through 2008.

(Figs. 3 and 4). Oil, however, is a nonrenewable resource and its supply will, at some point, decline. "Peak oil" refers to the time period (it can be one or several years) when global oil production reaches a maximum rate and then begins to decline. Conceptually, peak oil represents the point at which the world will transition from an expansionist industrial era, characterized by indefinitely expanding oil consumption, to an era defined by declining supplies of oil and, presumably, all those things we do with oil. As a result, peak oil represents a major problem for the U.S. (and most) economies, as it indicates that

oil supplies cannot increase with economic expansion in the long term.

It is not only the quantity of oil that is important, but also the cost of that oil. It is our ability to find, develop, and produce that oil for a reasonable energy and hence monetary cost that makes it so useful. Net energy is defined as the amount of energy remaining after the energy costs of getting and concentrating that energy are subtracted.[19] The economy gains zero net energy if we have to use just as much energy to develop a resource as we will garner from producing that resource. To that end,
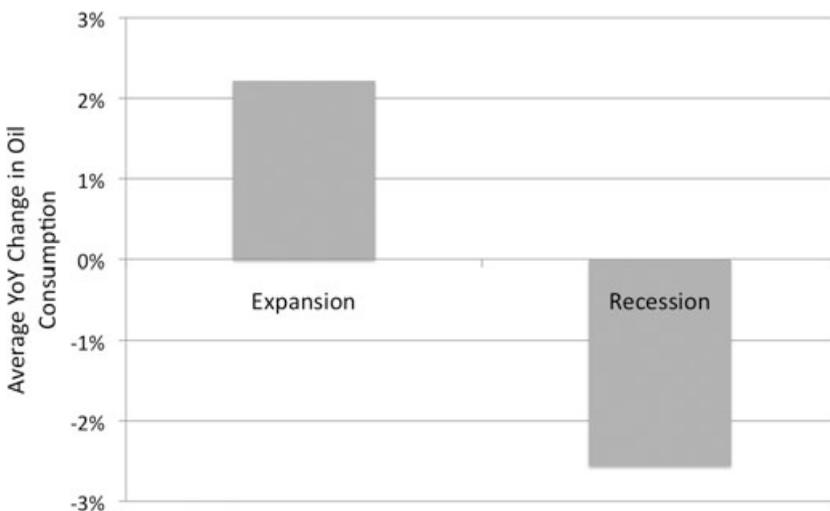

Figure 4. YoY percentage change in oil consumption averaged over expansionary and recessionary periods from 1970 through 2008.
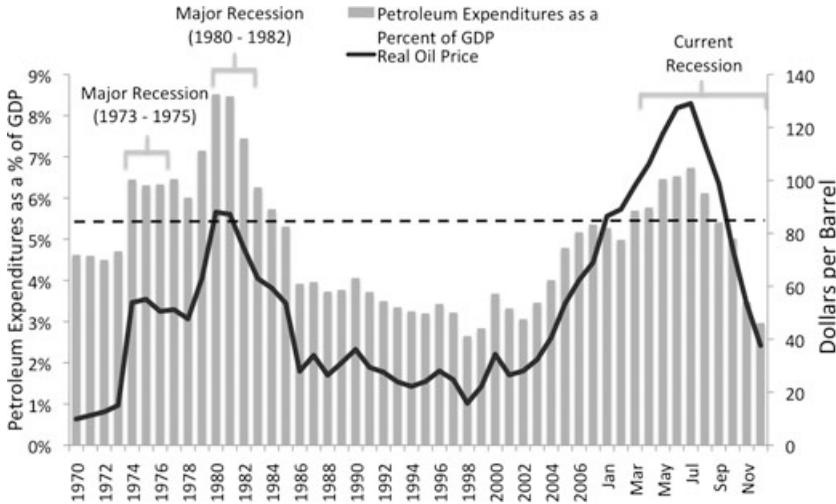
Figure 5. Petroleum expenditures as a percentage of GDP and real oil price. The dotted line represents the threshold above which the economy moves toward recessions. Petroleum expenditures includes distillate fuel oil, residual fuel oil, motor gasoline, liquified petroleum gas, and jet fuel.

energy resources that produce a high level of net energy are considered to be of higher value than those that produce a small amount of net energy.

Since oil consumption is important for economic growth, understanding how both peak oil and net energy will impact oil supply and price is important to understanding the ability of our economy to grow in the future. To that end, we will review both the theory and current status of peak oil and net energy as they pertain to oil supply, and then discuss how both of these may influence oil price.

Peak oil

The concept of peak oil originated from an analysis performed by M. King Hubbert in 1956.[20] Hubbert aggregated the production profiles of individual oil wells into a singular production profile for an entire oil field and found that the shape of the production profile could be estimated closely by a bell-shaped curve, with production (commonly in units of barrels per year) on the *y*-axis and time (years) on the *x*-axis (Fig. 6).[20] The notion of peak oil is derived from this curve, which has a distinct point at which production is at its highest. After this peak, the production of the field enters a phase of generally irreversible decline. The concept and the mathematics can be applied at many levels, including specific oilfields, regions, or globally. Global peak oil refers mainly to the peaking of global oil production, which is simply the aggregation of the

production profiles for all oil fields around the world into one production pattern over time.

It is sometimes possible, using very few parameters, to predict both the timing of a peak's occurrence and the level of production at the peak. In 1956, Hubbert[20] used his model to predict that the oil production of the lower 48 United States would peak in the late 1960s or early 1970s at a rate of roughly 3 billion barrels of oil (billion barrels of oil = gigabarrels of oil = Gbo) per year. Many in the industry claimed his predictions were ludicrous, and that U.S. oil production would increase indefinitely. But in fact oil production in the United States peaked in 1970 at a rate of roughly 3.5 Gbo per year. Hubbert's model was validated, within a reasonable margin of error, by the actual production data 14 years after his prediction. He later refined his model to its current form, called simply the "Hubbert Curve," and today it is used commonly to predict oil production from fields all over the world.

Hubbert[20] predicted that peak oil for the world would occur around 2000 based on an estimated ultimate recoverable quantity (EUR) for global oil of 1,250 Gbo. An analysis by Deffeyes predicted that global crude oil production would peak in 2003 based on an EUR of 2,120 Gbo.[2] Campbell estimated that the peak in global oil would occur in 2003, as well, but his estimate was based on an EUR of 1,800 Gbo.[2] Campbell and Deffeyes used models based on different data sets estimating global oil
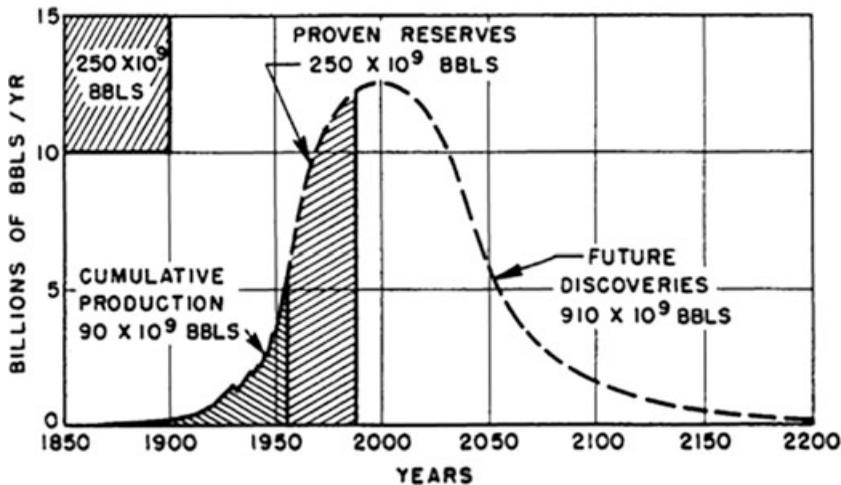
Figure 6. Hubbert curve of oil production for the world (from Hubbert).[20]

production and reserves, yielding the same peak year despite a large difference in EUR. A similar analysis by Campbell and Laherrere predicted that the peak in global oil production would occur at some point in the decade of 2000–2009 based on an EUR of roughly 1,850 Gbo.[3] Numerous other analyses have estimated the peak in global oil production to occur within the decades from 2000 to 2020.[21–24]

Despite these analyses, some researchers doubt that the world is even near a peak in global oil production.[25,26] One way to check whether a peak in oil production has occurred is to compare oil production data from fields around the world; a method that is more straightforward in theory than in practice, as the majority of global oil production has shifted from independent oil companies (IOCs), such as ExxonMobil, to nationalized oil companies (NOCs), such as Saudi Aramco. Today, NOCs produce over half of world's oil and control nearly 90% of the world's oil reserves, yet NOCs are not required to provide reserve estimates or any data whatsoever, and historically, much of the data that were reported have been suspect.[27,28] In the mid-1980s, for example, the Organization for Petroleum Exporting Countries (OPEC) changed its policy regulating production quotas so that each OPEC member could produce oil in proportion to their reserves—that is, countries with high reserves could produce more oil. Since all of these nations had large governmental debts or at least expenditures, each country wanted to sell more oil and hence was incentivized to have higher reserves. During this same period, the reserve estimates within OPEC increased by

300 Gbo without reporting any new major discoveries. Many analysts today still doubt the validity of these increases.[3]

Due to these inaccuracies or rather unknowns surrounding OPEC and NOC data, determining the exact year of peak oil from estimates of production and reserves may be possible only retroactively. But such a determination is inessential because oil production is likely to plateau for several years both before and after the actual peak, and it is during this period that oil supply may fall short of demand.[29] Estimating when oil production enters this plateau era is useful, as it may be an early sign of peak oil.

There are three lines of evidence that society appears to be at or at least approaching peak oil. These are (1) production is outpacing discoveries, as global society consumes at least two barrels of oil for every new barrel discovered; (2) production remained flat during a four-year period of increasing oil prices; and (3) most of the easy-to-find and easy-to-produce oil has been found and produced—Ghawar in Saudi Arabia, the world's largest oil field, was discovered in 1948 and society has yet to find a field of nearly the same caliber, despite advances in exploration technology. Details of each of these lines of evidence follow.

The first line of evidence is related to the fact that oil production lags discoveries by roughly 10 years.[1,20,29] That is to say, discoveries made today will begin to impact oil supply in 10 years. Using this lag effect, Hubbert was able to predict in 1956 that the peak in oil production for the lower 48 United States would occur around 1970—the data

Table 2. Oil demand in 2008 and projected for 2030, according to four different sources, and the average annual rate of oil discovery

	Oil Demand		Average annual rate of discovery, 1998–2007	Discovered to consumed, 2008	Projected: discovered to consumed, 2030
	2008	Projected 2030			
Dargay and Gately	30	49	15	1–2	1–3.3
IEA	30	39	15	1–2	1–2.6
EIA	30	39	15	1–2	1–2.6
OPEC	30	39	15	1–2	1–2.6

Note: Units for oil demand are in gigabarrels of oil.
Source: Data for projected demand from Dargay and Gately,[30] and data for discoveries are from Harper[31] and Jackson.[32]
IEA, International Energy Agency; EIA, Energy Information Administration

were already in! With this in mind, we can look at recent discoveries to make estimates of future production. From 1998 to 2007, the annual rate of discovery of oil was 15 Gbo per year while the consumption of oil in 2008 was 30 Gbo, indicating that in 2008 the world produced and consumed at least 2 bbl for every barrel it found.[32,33] Oil demand is projected to be 39–49 Gbo per year by 2030, and, if the rate of discoveries remains constant, the world will be consuming between 2.6 and 3.3 bbl of oil for every barrel found (Table 2).[30,33] From these data, it is clear that discoveries are being outpaced by production—a condition indicative of peak oil.

Second, from 2004 to 2008 oil production leveled off even while the price of oil increased from $30 to $142/bbl (Fig. 7). Basic supply and demand economics indicates that supply should increase given an increase in price; yet oil supply remained flat. Further evidence can be seen in the estimates of OPEC spare capacity for the same time period. OPEC spare capacity decreased from almost 6 million barrels per day (mbpd) in 2002 to less than 2 mbpd in 2008 (Fig. 8).[34] Thus, any increases in global oil production that may have occurred between 2004 and 2008 are probably attributable to the drawdown of OPEC spare capacity rather than
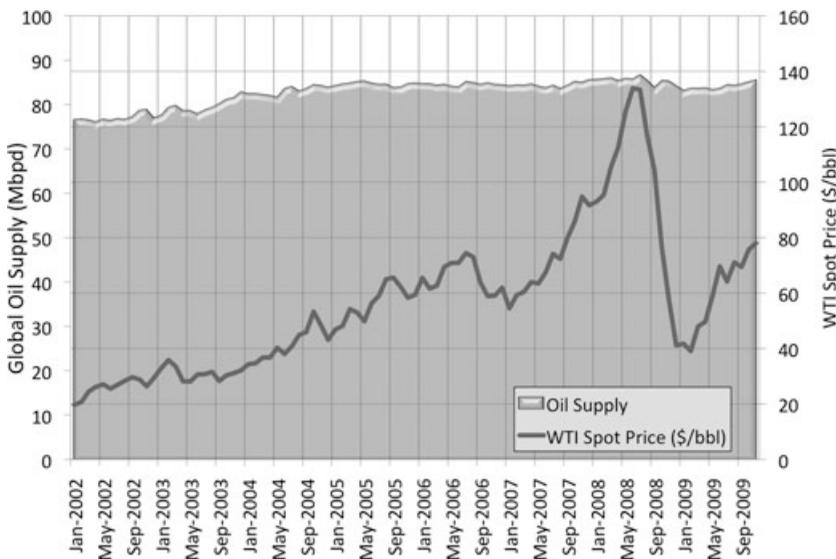

Figure 7. Global oil supply by month from January 2002 through December 2009 and monthly West Texas Intermediate (WTI) spot prices in dollars.
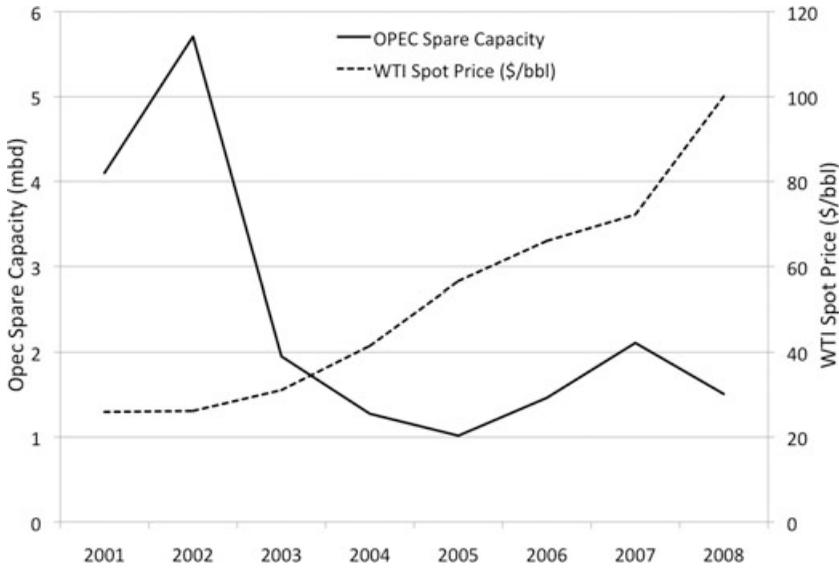
Figure 8. Annual estimates of OPEC spare capacity and average West Texas Intermediate (WTI) spot prices ($/bbl) from 2001 through 2008. Data on OPEC spare capacity from McKinsey.[34]

new production coming online. Given these data, it seems reasonable to assume that stagnating oil production from 2004 to 2008, in an era with all-time high prices, was due to the fact that the global oil industry was producing oil at its maximum rate—another condition indicative of peak oil.

Third, most of the easy-to-find and easy-to-produce oil has already been found and produced.[3] Global oil discoveries peaked during the 1960s and have declined steadily since (Fig. 9). In addition

to finding less oil, new discoveries are located increasingly in areas that are geologically harder to produce, such as deep offshore areas. Discoveries in deepwater areas increased from under 10% of total discoveries in 1990 to nearly 60% by 2005 (Fig. 10). These three lines of evidence suggest that society is entering the era of peak oil. Note, we are simply stating that the evidence indicates that oil supplies were constrained from 2004 to 2008, and that the most likely explanation is that the supply of
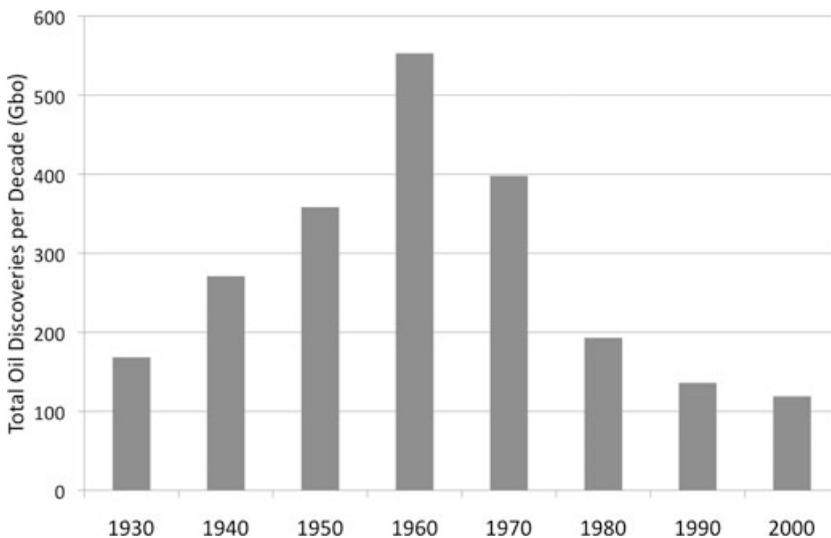

Figure 9. Total oil discoveries per decade from 1930 through 2007, in gigabarrels of oil (Gbo). Data from Jackson.[32]
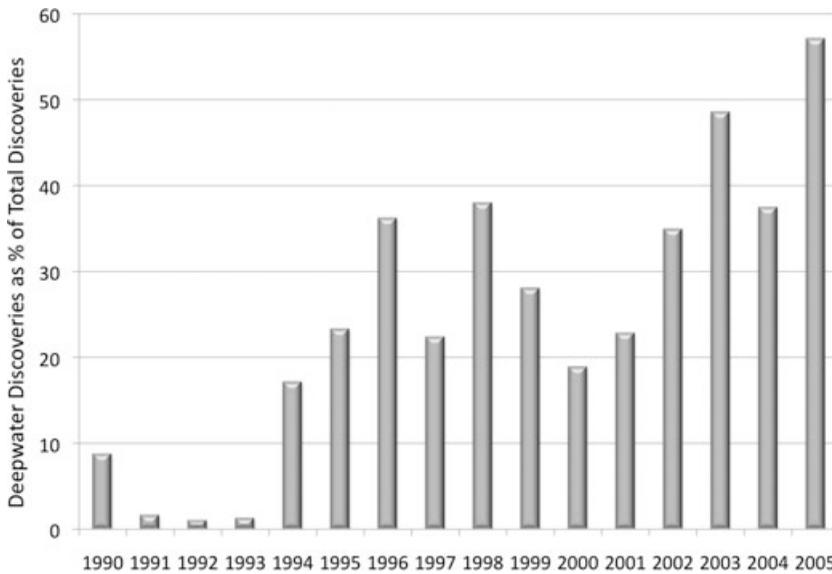
Figure 10. Deepwater oil discoveries as a percentage of total discoveries from 1990 through 2005. Data from Jackson.[32]

conventional crude oil is nearing (or possibly past) its peak. Other explanations for the constraint in oil supply from 2004 to 2008 is a lack of investment in infrastructure from the oil industry, but we could not find much evidence to support his claim, especially considering the large investments made into the oil sands and deepwater exploration during this period.

Summary of peak oil. Long-term economic growth has been correlated with increasing oil consumption, but the evidence presented here indicates that global society is entering an era in which prolonged increases in the production of oil are not possible. Despite not knowing the exact date of the peak, we can conclude with confidence that we are entering an era of at least a constrained oil supply, based on the three lines of evidence summarized above.

Critiques of peak oil theory and our response. There are two main criticisms of peak oil theory that are often cited in the literature. The first asserts that peak oil theory is fundamentally flawed because it assumes a fixed value for EUR when in fact the amount of EUR depends upon a number of factors that are not fixed, such as technology, price, and infrastructure.[25,26] The second major criticism is that society will find substitutes for oil as oil grows scarce.[26,35–37] Both of these criticisms are used by

peak oil naysayers to claim that peak oil is a red herring. We address both of these concerns in turn.

First, we cannot produce what we cannot find. Global discoveries have been in a steady decline since the peak in 1948, or the decadal peak in the 1960s, despite advances in technology (Fig. 9). Others argue that as the price of oil increases known sources of oil that were previously too expensive to develop will become economical. To some extent this is true: oil sand development in Canada, for example, is expensive and economically feasible at high oil prices only. However, the oil sands are not conventional oil sources and are not new discoveries, and are already incorporated into many models of future oil supply.[3]

Even if the value for EUR is incorrect, this would only delay the issue of peak oil, not change it.[24] Bartlett calculates that for every additional billion barrels of oil we find beyond two trillion barrels delays the peak in global oil production by only 5.5 days.[24] He also found that doubling the EUR (to four trillion barrels) delays the peak by only 26 years. We came to a similar conclusion using the data from Campbell and Laherrere.[3] For example, if we assume that the EUR is twice that assumed by Campbell and Laherrere, that is, EUR is 3,700 Gbo (an almost impossibly large increase in EUR and one that the literature has not supported), and that oil consumption grows by 2% per year, then global oil production

would peak in 2032 versus 2005 (Fig. 11); that is, the peak is delayed roughly 27 years. In sum, our best estimates place the peak within the decade of 2000–2010, and even if these best estimates are far off the mark, the peak will still occur within a few decades' time.

The second critique of peak oil states that as oil becomes scarce we can substitute toward other energy sources. We argue that there is no substitute for conventional oil that is of the same quantity, quality, and available for the same price. The closest substitutes for conventional oil currently in large-scale production are the oil sands of Canada and biofuels, produced mainly from corn and sugarcane. The oil sands present a vast amount of potential energy, but it is in a less accessible form than conventional oil. The oil sands must be heated and refined just to form crude oil and then refined further to form the various crude oil derivatives. Estimates from Cambridge Energy Research Associates show that the cost of production for the oil sands is roughly $85/bbl, which is more than double the average price of oil during expansionary periods ($37/bbl).[38] The usual assumption is that the oil sands will be rate limited, not resource limited, because of their large demands for water and natural gas and their large environmental impacts.[3] So, even though there

are large amounts of potential energy, production of oil sands cannot be increased enough to offset a large decline in conventional oil production.

Biofuels are recent plant material that has been converted through some combination of chemical and/or thermal processes into a liquid fuel. The main fuel products from these processes are biodiesel, or more commonly ethanol. There are numerous reasons why alcohols do not produce as good fuel as gasoline, and we present here two. First, the energy density of ethanol is only about two-thirds that of gasoline. Second, and most compelling, the energy contained within the biofuel product is nearly the same as the energy used to produce the biofuel. In other words, producing biofuels provides roughly zero net energy to society.[39–43] Oil, on the other hand, produces roughly 18 units of energy per unit invested, and gasoline roughly 10 units per unit invested.[44,45] These points indicate that gasoline and biofuels are imperfect substitutes and place doubt on their ability to replace oil.

Another reason indicating that substituting for oil will be difficult is that it takes a very long time to construct the infrastructure to move from one source of primary energy to another. Marchetti analyzed the time it took global society to transition from wood to coal and subsequently from coal to oil
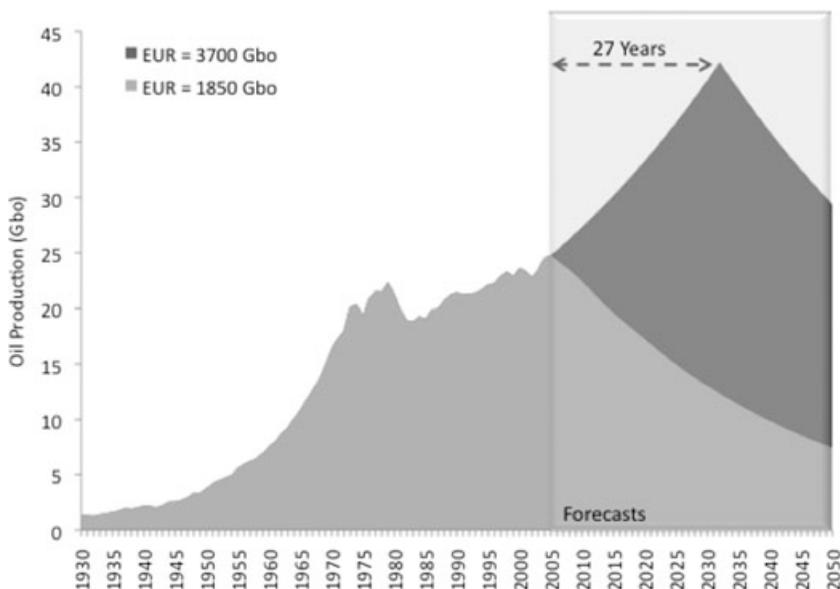

Figure 11. Two estimates of global conventional oil production: the light gray estimate is based on an EUR of 1,850 Gb, and the dark gray estimate is based on an EUR of 3,700 Gb. In other words, doubling the EUR delays the peak in global oil production by 27 years.

and found that it takes about a century for society to increase its adoption of a primary energy substitute from 1% to 50% of market capacity.[46] Thus, even if society adopts alternative energy quickly, it will still take decades to substitute for just half of the oil use in the world.

Hirsch *et al.* came to a similar conclusion when examining the specific strategies that the United States might take to mitigate its oil dependence.[47] They examined numerous, large-scale methods by which the United States could substitute for conventional oil, including: (1) conservation—implementing higher efficiency energy equipment, that is, high-mileage automobiles; (2) gas-to-liquids; (3) fuel switching to electricity; and (4) coal liquefaction. Their main conclusion is that "waiting until world oil production peaks before taking crash program action leaves the world with a significant liquid fuel deficit for more than two decades"(p. 59).[47]

In sum, neither changing the EUR used in peak oil analysis nor trying to substitute for oil repeals the general argument put forth by peak oil theorists, that is, peak oil will restrict the supply of oil in the near future.

Energy return on investment and net energy

The following discussion of net energy is an extension of the third main point from the peak oil section: how a shift from easy-to-access oil to hard-to-access oil is changing the net energy delivered to society and how this may exacerbate the effects of peak oil on economic growth. Howard Odum noted that "the true value of energy to society is the net energy" (p. 220).[19] But the impacts of net energy on peak oil and economic growth are often overlooked and/or misunderstood. Fundamentally, net energy measures the useful energy for society, expanding the supply of net energy aids economic growth while decreasing the supply of net energy constricts economic growth.

There has been a surge recently in the amount of literature published related to net energy, driven mainly by escalating oil prices from 2004 to 2008 and the subsequent growth in the alternative energy market.[16] Most studies use a statistic related to net energy called energy return on investment (EROI),[c]

which is defined as the gross energy produced divided by the energy invested to produce the gross energy and is sometimes referred to as net energy ratio or energy return on energy investment.[16] EROI is calculated as follows:

$$\text{EROI} = \frac{\text{Gross Energy Produced}}{\text{Energy Invested to get that Energy}} \quad (1)$$

Net energy is calculated as

$$\text{Net Energy} = \text{Gross Energy Produced} \\ - \text{Energy Invested to get that Energy} \quad (2)$$

The most important mathematical distinction between EROI and net energy is that EROI is a unitless ratio used to compare outputs to inputs while net energy is a finite amount of energy with a defined unit. It is also important, at this point, to note the difference between primary energy sources[d] and energy carriers (adapted from Ref. 48).[e] A primary energy source is an energy source that exists in nature and can be used to generate energy carriers (e.g., solar radiation, fossil fuels, or waterfalls). An energy carrier is a vector derived from a primary energy source (e.g., electricity, gasoline, or steam).[48] Thus, the calculation of EROI must use energy inputs and outputs in units assigned to energy carriers.

There is a clear trend in the literature on EROI of global oil production toward lower EROIs. Gagnon *et al.* report that the EROI for global oil extraction declined from 36:1 in the 1990s to 18:1 in 2008.[44] This downward trend results from at least two factors: First, increasingly supplies of oil originate from sources that are inherently more energy intensive to produce, simply because firms develop cheaper resources before expensive ones. For example, in 1990 only 2% but by 2005 60% of discoveries were located in ultradeepwater locations (Fig. 10). Second, enhanced oil recovery techniques are being implemented increasingly in the world's largest conventional oil fields. For example, nitrogen injection was initiated in the once supergiant Cantarell field in Mexico in 2000, which boosted production for 4 years, but since 2004, production from the field

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[c] Energy produced from an energy extraction process divided by the energy used in extraction.

[d] Physical energy sources that exist in nature and that are used to generate energy carriers (e.g., solar radiation, crude oil, coal, natural gas, and waterfalls).
[e] Energy vectors derived from primary energy sources (e.g., electricity, gasoline, and steam).

has declined precipitously (Fig. 12). Although enhanced oil recovery techniques increase production in the short term, they also increase significantly the energy inputs to production, offsetting much of the energy gain for society.

Declining EROIs mean that more energy is required to get energy, and therefore the amount of net energy provided to society from an oil field decreases. Take, for example, the following two hypothetical societies (Figs. 13A and 13B). Society A has an energy source that can be extracted at an EROI of 18. Society B has an energy source that can be extracted at an EROI of 1.2. In this example both societies extract 100 units of energy, but due to the different EROIs with which that energy is extracted, the amount of net energy provided to society is much different. Society A must invest six units of energy to maintain the energy investments needed to extract 100 units of energy, while Society B must invest 80 units of energy. The end result is that Society A has 96 units of net energy to allocate to whichever means it desires, while Society B has only 20 units of net energy. The relation between net and gross energy is summarized in equations 3–5 (equations 4 and 5 adapted from Refs. 49 and 50):

$$\text{Gross Energy Produced} = \text{Net Energy} \quad (3)$$
$$+ \text{Investment Energy}$$
$$\text{Net Energy} = \text{Gross Energy} * [(\text{EROI} - 1)/\text{EROI}] \quad (4)$$

$$\text{Gross Energy} = \text{Net Energy}/[(\text{EROI} - 1)/\text{EROI}] \quad (5)$$

Another way to examine these scenarios is to look at how much gross energy must be extracted to maintain a constant supply of net energy to society. To supply society with 100 units of net energy, through an extraction process that has an EROI of 18, society would need to extract 106 units of gross energy (Fig. 14A). Six units are used to maintain the investments associated with energy extraction. To deliver the same amount of net energy from a process with an EROI of 1.2, society would need to produce 600 units of gross energy (Fig. 14B). Most of the gross energy produced (500 units) is needed to maintain the investments associated with energy extraction. But all of the investment, both monetary and energy, is nonetheless needed to maintain the flow of energy that society needs. Thus, those who argue that we should be running our energy economy on, for example, corn-derived ethanol with an EROI of 1.2 need to think of these implications.

Declining EROIs exacerbate oil depletion by requiring an acceleration of the extraction of resources to simply offset a decline in EROI. For example, let's assume that today's oil is produced at an EROI of 18:1. That means that of the 30.8 Gb of gross oil produced in 2008, 29.1 Gb were delivered to society as "net oil," using equation 4 to calculate the amount of net oil given gross oil and EROI. Let's also assume that the world has roughly 925 Gb of oil remaining
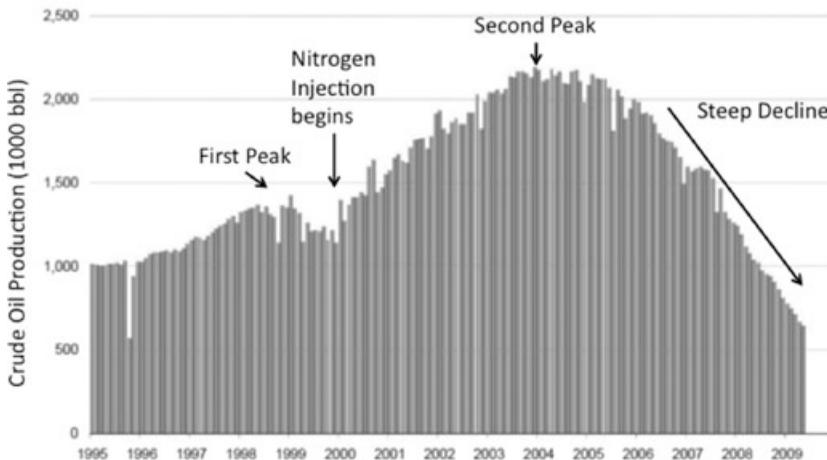

Figure 12. Production from the Cantarell oil field in the Mexican Gulf of Mexico. Source: Energy Information System, Federal Government of Mexico, published on 7/27/09. http://graphics.thomsonreuters.com/ce-insight/CANTARELL.pdf.
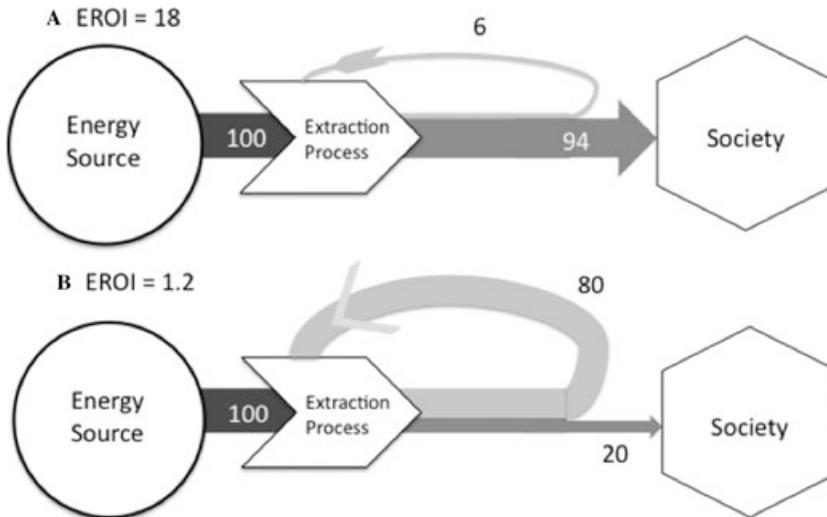
Figure 13. The flow of energy from the point of extraction to society accounting for the energy cost of extraction. Values were calculated using equation 4, assuming 100 units are extracted at an EROI of 18 for A and 1.2 for B.

(50% of the EUR of 1,850 Gb).[3] If society were to maintain that rate of consumption of oil (29.1 Gb), then we would have 30 years of conventional oil remaining (925/30.8). However, if the EROI were to decrease by half (9), then we would have only 27 years remaining (925/34.6), due to the lower EROI, the gross amount of oil extracted must increase to maintain a constant amount of net energy delivered to society. Or, if the EROI were to decrease to 3:1, then we would have only 20 years of conventional
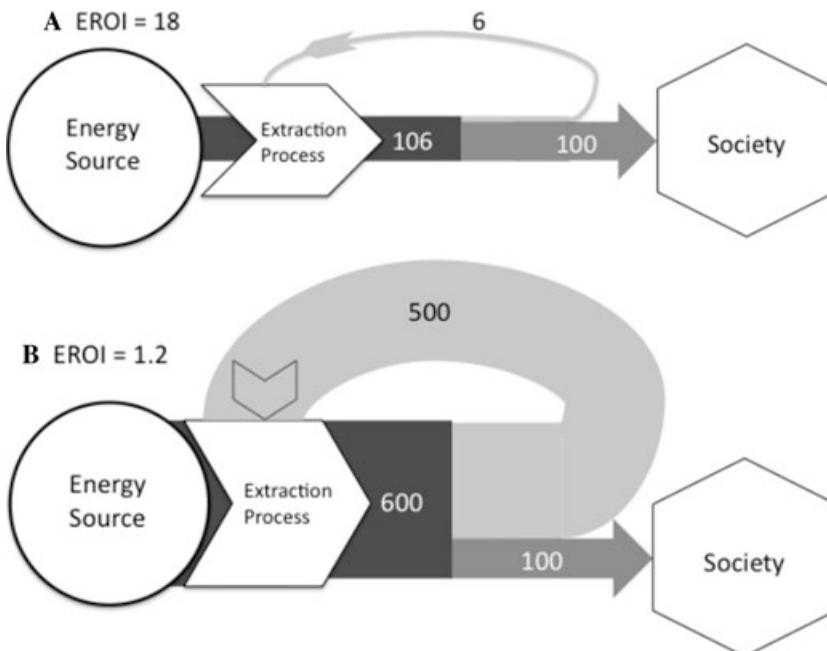

Figure 14. The flow of energy from the point of extraction to society accounting for the energy cost of extraction. Values were calculated using equation 5, assuming that 100 units are delivered to society, and the energy source is extracted at an EROI of 18 for A and 1.2 for B.

oil remaining, at current levels of consumption (925/46.2). If consumption of conventional oil increases we will exhaust our remaining crude oil supplies even faster.

Summary of net energy. Both the literature and data indicate that the EROI for global oil production is declining. According to the algebraic relation described in equations 3–5, maintaining the flow of net energy to society given declining EROIs will require an increase in the extraction of gross energy, accelerating the depletion of oil. This means that it will be very difficult to offset peak oil by finding and developing new, low EROI fields because new fields must produce enough oil to not only match the depletion of the existing field stock but also to overcome the decline in EROI. As a result, we have anywhere between 20 and 30 years of conventional oil remaining at current levels of consumption, depending upon the average EROI of oil production.

The depletion of conventional oil will most likely follow an exponential decline, as peak oil theory suggests, taking much longer for production to completely exhaust supplies.[3] Nonetheless, the conditions described herein will not change as oil production declines, that is, new sources of oil will be harder to produce on average leading to lower net energy gain per field.

Peak oil, net energy, and oil price

The analyses presented in this review indicate that economic growth over the past 40 years has required both an increasing oil supply and also a relatively low oil price. So far the discussion has focused almost exclusively on the supply side of this argument, concluding that over the past 40 years oil prices remained relatively low, due in part to the fact that there were amply supplies of high EROI oil available for extraction. Society is entering the era of peak oil and the supply of conventional oil (high EROI) has or will plateau and eventually decline. In addition the EROI of oil production is declining, requiring more energy just to offset the declining amount of energy. Thus, low EROI oil indicates that there will be high oil prices in the future.

Forecasting the price of oil, however, is a much more difficult endeavor as oil price depends, in theory, on the supply and demand for oil at a given moment in time. What we can examine with some accuracy is the cost of production of various sources of oil, in order to calculate the price at which different types of oil resources become economical (Fig. 15). In theory, if the price of oil is below the cost of production, then most producers will cease operation. If we examine the cost of production in the areas in which we are currently discovering oil, hence the areas that will provide the future supply of oil, we
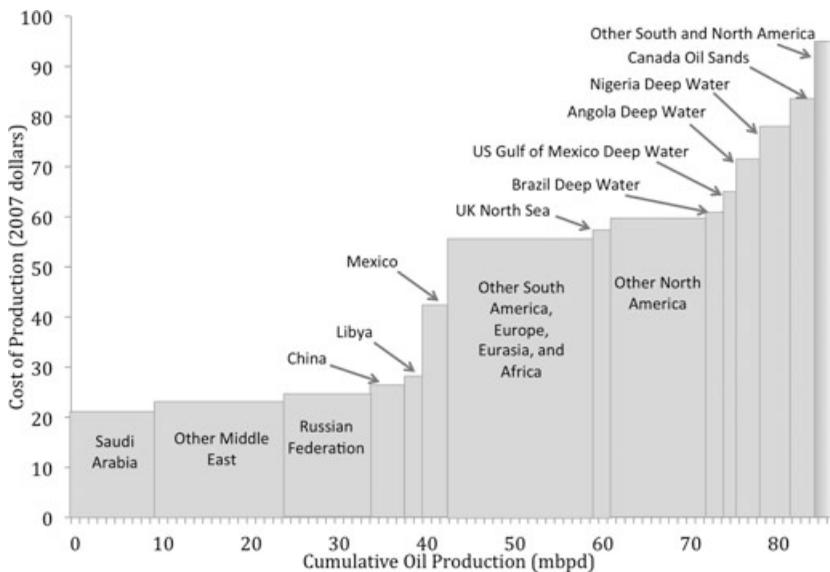

Figure 15. Estimations of the cost of oil production for various locations and types of resources around the world. Data from CERA.[38]

can calculate a theoretical floor price below which an increase in oil supply is unlikely.

Roughly 60% of the oil discoveries in 2005 were in deepwater locations (Fig. 10). Based on estimates from CERA,[38] and the cost of developing that oil is between $60 and $85/bbl depending on the specific deep water province. Oil prices therefore, at a minimum, must exceed roughly $60/bbl to support the development of even the best deepwater resources. The average price of oil during recessionary periods has been $57/bbl, so it seems that increasing oil production in the future will occur only at recessionary prices. All of this indicates that an expensive oil future is necessary if we are to produce the remaining oil resources, and, as a consequence, the economic growth witnessed by the United States and globe over the past 40 years will be difficult to realize in the future.

Since EROI is a measure of the efficiency with which we use energy to extract energy resources from the environment, it can be used as a rough proxy to estimate whether the cost of production of a particular resource will be high or low. For example, the oil sands have an EROI of roughly 3:1, whereas the production of conventional crude oil has an average EROI of 18:1. The production

costs for oil sands are roughly $85/bbl compared to $20/bbl for Saudi Arabian conventional crude.[38] As we can see from these data there is an inverse relation between EROI and price, indicating that low EROI resources are generally more expensive to develop whereas high EROI resources are generally inexpensive to develop (Fig. 16). As oil production continues, we can expect to move further toward the upper right of Figure 16.

Summary

The main conclusions to draw from this discussion are that (1) over the past 40 years, economic growth has required increasing oil production; (2) the supply of high EROI oil cannot increase much beyond current levels for a prolonged period of time; (3) the average global EROI of oil production will almost certainly continue to decline as we search for new sources of oil in the only places we have left—deep water, arctic, and other hostile environments; (4) we have globally roughly 20–30 years of conventional oil remaining at current rates of consumption and current EROIs, and even less if oil consumption increases and/or EROI decreases; (5) increasing oil supply in the future
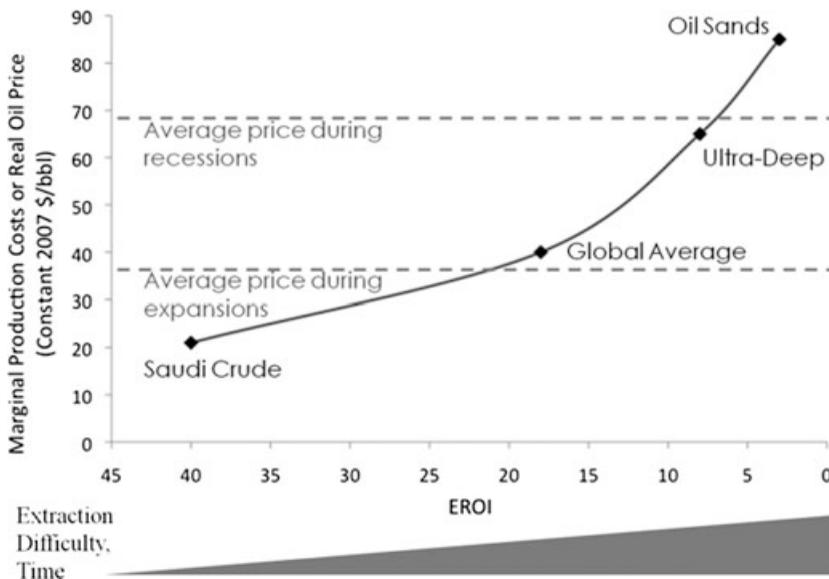

Figure 16. Oil production costs from various sources as a function of the EROI of those sources. The dotted lines represent the real oil price averaged over both recessions and expansions during the period from 1970 through 2008. EROI data for oil sands come from Murphy and Hall, the EROI values for both Saudi Crude and ultradeep water were interpolated from other EROI data in Murphy and Hall, data on the EROI of average global oil production are from Gagnon *et al.*, and the data on the cost of production come from CERA.[16,38,44]

will require a higher oil price because mostly only high-cost resources remain to be discovered; and (6) using oil-based economic growth as a solution to recessions is untenable in the long term, as both the gross and net supplies of oil has or will begin, at some point, an irreversible decline.

Synthesis

We can divide the oil age into three eras, each with a distinct model of economic production driven by the availability of inexpensive oil. The three eras are (1) prepeak, (2) peak, and (3) postpeak, and we will describe each in turn (Fig. 17).

The prepeak era is defined by exponentially increasing supplies of oil, which is the era from oil discovery in 1861 through the peak in oil discoveries in the 1960s (i.e., prepeak = 1861–1969). Oil discoveries continually outpaced production during this era, and the discoveries that were made had very high EROIs. In fact, the EROI of oil production did not change significantly during this era. For example, the average EROI of the East Texas Oil Field, discovered in 1930, was probably comparable to that of Ghawar, discovered in 1948. And since increasing demand for oil was met with oil supplies from these high EROI resources, the inflation-adjusted price of oil over the period of 1861–1969 remained low: $23/bbl (in 2008 dollars) on average.

Abundant, inexpensive oil led to a model of economic growth during the prepeak era that can be described by the following cycle of events (Fig. 18): (1) increasing oil consumption led to economic growth and an increasing demand for oil; (2) increasing demand for oil led to increasing production of oil; initially oil came from high EROI sources; therefore, the cost of production remained low during this period, depressing oil price; and (3) low oil prices led to increasing oil consumption and higher economic output and the cycle began again. This cycle continued indefinitely as long as all oil was cheap to produce, which was the case until the supply of oil became constrained or the EROI of oil declined significantly, both of which occurred during the subsequent peak era.

The peak era began after the peak in global discoveries (1970) and continues through the peak in global production (sometime between 2000 and 2020). Although discoveries had peaked during the 1960s, the production of oil continued to increase, though at a slower rate, during this era due to the fact that more oil was discovered than produced during the prepeak era. Thus, the peak era can be described as beginning during an era of diminishing marginal returns to production and ending after the peak in production.

In addition to a dwindling number of discoveries, the EROI of the discoveries that were made
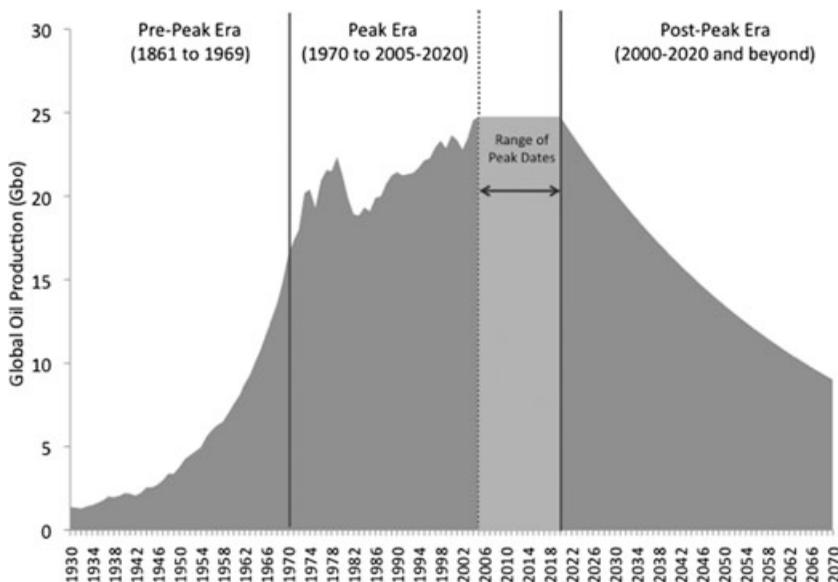

Figure 17. Division of the age of oil into three eras.

Pre-Peak Model of Economic Growth

1. Increasing GDP and Oil Demand ➞ **2. New High EROI Resources**

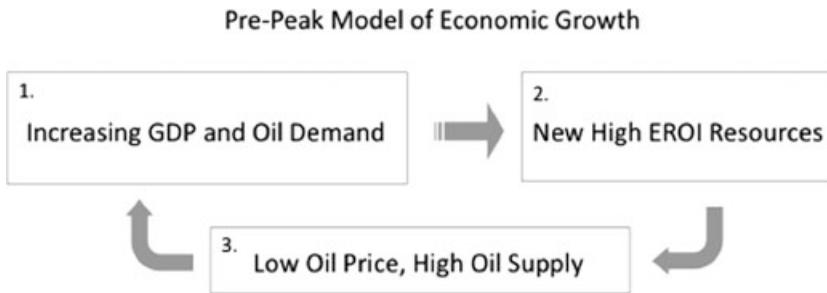**3. Low Oil Price, High Oil Supply**

Figure 18. Prepeak model of economic growth.

after the 1960s tended also to be lower. Prudhoe Bay, for example, was discovered in 1968 but production did not begin until the Alaska pipeline was finished nearly a decade later. Although Prudhoe Bay had vast reserves, it was certainly more costly to develop than East Texas because of pipeline construction, among other expenses. In the 1980s, the United States began to rely increasingly on imported oil, adding transportation costs and foreign levies to the total cost of the U.S. oil supply. Today, we are expanding production to ultradeep water and to unconventional sources of oil, both of which have much higher costs. Since the costs have increased since 1970, predictably, so has the price. The average inflation-adjusted price of oil from 1970 through 2008 was $43/bbl, almost double the previous era. In other words, it was not the depletion of oil per se, but the depletion of high EROI oil that contributed to an increase in the price of oil over the long term.

Due, apparently, to the depletion of high EROI oil, the economic model for the peak era, that is, roughly 1970–2020, is much different than the pre-peak model and can be described by the following feedbacks (Fig. 19): (1) economic growth increases oil demand; (2) higher oil demand increases oil pro-

duction from lower EROI resources; (3) increasing extraction costs leads to higher oil prices; (4) higher oil prices stall economic growth or cause economic contractions; (5) economic contraction leads to lower oil demand; and (6) lower oil demand leads to lower oil prices, which spur another short bout of economic growth until this cycle repeats itself. This system of insidious feedbacks is aptly described as a growth paradox: maintaining business as usual economic growth will require the production of new sources of oil, yet the only sources of oil remaining require high oil prices, thus hampering economic growth.

The growth paradox leads to a highly volatile economy that oscillates frequently between expansion and contraction periods, and as a result, there may appear to be numerous peaks in oil production. In terms of business cycles, the main difference between the pre and peak era models is that business cycles appear as oscillations around an increasing trend in the prepeak model while during the peak era model they appear as oscillations around a flat trend. Colin Campbell referred to this as an undulating plateau.[51]

We predict that business cycles in the postpeak era, that is, the period when oil production decreases

Peak Era Model of Economic Growth

1. Increasing GDP and Oil Demand ➞ **2. New Low EROI Resources** ➞ **3. High Oil Price, High Oil supply**

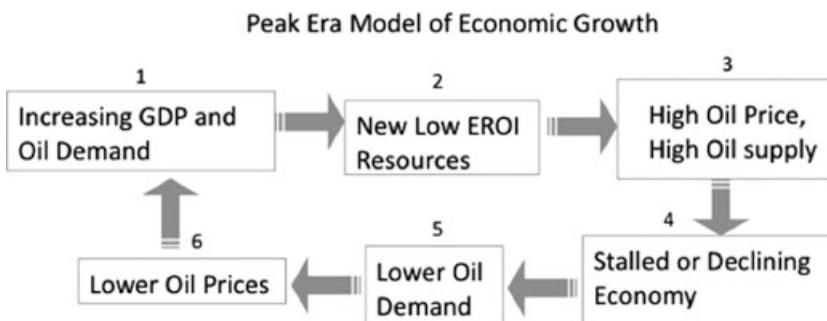**6. Lower Oil Prices** ⬅ **5. Lower Oil Demand** ⬅ **4. Stalled or Declining Economy**

Figure 19. Peak era model of the economy.

on average year after year (2020+), will appear as oscillations around a declining trend. It is difficult to predict what the economic model of the post-peak era will look like, but it will undoubtedly be similar to the peak era model, as oil production and the EROI of oil production will both continue to decline.

It is important to emphasize that these models assume that society will continue to pursue business-as-usual economic growth, that is, the models assume that businesspersons will continue to assume that oil demand will continue to increase in the future. The model also ignores the increasingly important and intricate role that debt accumulation has in the greater energy economy, or the role that economies of scale may play when transitioning from a mature fossil fuel industry to an immature renewable energy industry.

But what if economic growth was no longer the goal? What if society began to emphasize energy conservation over energy consumption? Unlike oil supply, oil demand is not governed by depletion, and incentivizing populations to make incremental changes that decrease oil consumption can completely alter the relation between oil and the economy that was described in the aforementioned models. Decreasing oil consumption in the United States by even 10% would release nearly 2 million barrels of oil onto the global oil markets each day.

For the economy of the United States and almost every other nation, the prospects for future, oil-based economic growth are bleak. Maintaining the status quo of growth economics based on an oil energy base is simply not possible for more than a decade or two at most, presuming that trade lines and international politics remain amenable. For the United States, which is currently in the deepest recession since the Great Depression, it seems highly unlikely that oil production can increase enough, for a long enough period of time, to grow the economy from this recession, let alone any future recessions. Furthermore, even if oil production can increase in the near term, the price of oil needed to maintain that production will be high enough on its own to incite a recession. Taken together, it seems clear that the economic growth of the past 40 years will not continue for the next 40 years unless there is some remarkable change in how we manage our economy.

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Conflicts of interest

The authors declare no conflicts of interest.

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