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Revisiting Hafemeister's science and society tests

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We revisit a series of papers on science and society issues by David Hafemeister in the 1970s and 1980s. The emphasis in the present work is on world oil production limits and some consequences of various possible scenarios for the near future. Some of the data and scenarios used by Hafemeister are updated for U.S. oil production in the past two decades, and extended to an analysis of a peak in world oil production in the future. We discuss some simple scenarios for future energy use patterns and look at the consequence of these scenarios as world oil production begins to decline. We also provide a list of resources for critical investigations of natural resource extraction and depletion patterns.

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I. INTRODUCTION

In several papers published in this journal in the 1970s and 1980s, David Hafemeister presented a series of "Science and society tests," including papers on "The energy crisis,"[1] "Transportation,"[2] "The 94th Congress,"[3] "Energy economics,"[4] and "Energy conservation."[5] A key paper in the same vein was Bartlett's "Forgotten fundamentals of the energy crisis."[6] More recently there has been an increasing awareness[7] of the possibility that our fossil fuel resources might not keep pace with increasing world consumption. In this paper we revisit some of the problems posed by Hafemeister, take a look at how the concepts have stood the test of time, and update his models where necessary.

One of the main concerns of this paper will involve a shift in emphasis from United States resource (principally petroleum products) extraction, to world production and consumption patterns. A clear result of the peak in oil production in the United States in the early 1970s is that imported oil became a substitute for domestic petroleum products. There is growing concern that we are approaching a peak in world oil production within the next 20 years, if not sooner. Furthermore, it appears that natural gas reserves in North America might not be as extensive as was thought only a few years ago. Both U.S. and Canadian production of natural gas appear to have been declining slightly for several years in spite of increasing prices, drilling activity, and demand. It thus becomes interesting to look for substitutes once again, which implies quickly finding replacements for the extremely high energy density fuel on which our industrialized societies are dependent.

In addition to the "back-of-the-envelope" calculations that helped to make the papers by Hafemeister so interesting, we will use some simple spreadsheet-based models in which the parameters can be easily changed to test various assumptions. Finally, we will point out some useful resources that can be used to quickly find relevant data. Much of the available information is in non-SI units, but we have made an attempt to include commonly used units and SI units for every problem.

It will be useful to include here a set of energy unit conversions for easy reference. In Table I are shown not only conversions between metric and English units of energy, but also energy equivalents for different types of fossil fuels, along with commonly used energy industry units.

II. HUBBERT'S PEAK AND OIL PRODUCTION

We begin our investigation of the production of energy resources by looking at what appears at first glance to be simple questions: How much oil is there in the world, and how long will it last? In 1956 a petroleum geologist named M. King Hubbert made the startling prediction that the production of oil in the continental United States would probably reach its maximum by the early 1970s. Because oil production at the time had been increasing steadily for a century at a rate of several percent per year, Hubbert's prediction appeared to many petroleum specialists to be unreasonable. Continental U.S. oil production did reach a peak in 1970, a milestone that was fully perceived only a few years after the fact, because oil production fluctuates for many reasons other than petroleum geology. The name "Hubbert's peak" has been given to the phenomenon of peak oil production.

Hubbert wrote many articles over the years in which he explained some of the methodology he used in arriving at his predictions for peak oil production in the U.S., and for the possibility of peak oil production in the world as a whole at some time in the future.[8] Several points should be made at the outset. There are many different sources of oil (for example, conventional on-shore drilling, off-shore deep-water drilling, and tar sands) and different authors use more or less strict definitions of which oil types "count." We will try to be explicit about the accounting methods used. In general, once the oil is in a form in which it can be sent to a refinery, the provenance is not important, as all oils are equivalent. A basic point is that all of the fossil fuels are finite, and therefore any production of this resource leads to depletion. Production increases initially from a low level when exploitation of the resource begins. When the resource is nearing depletion, production is again very low. In between these two extremes there must be a maximum production level. The question is when that maximum will occur and how high the maximum rate of production will be.

In the following set of problems we investigate the range of likely dates of world peak oil production, as well as the rate of production under different possible scenarios.

Problem 1. (a) Given available data for U.S. oil production, use a Gaussian function and a logistic model to describe production as a function of time. (b) Find the estimated ultimately recoverable oil in the U.S. (c) How much difference did the opening of the Alaskan reserves (unknown to Hub-

Table I. Energy units used in this paper, along with the energy content of various fossil fuels.

1 KWh = 3414 BTU; 1 BTU = 1055 J
1 Quad = 10^{15} BTU = 1.06×10^{18} J = 1.06 EJ
1 kilocalorie(kcal) = 4.187 kJ = 3.968 BTU
1 ton of oil equivalent (toe) ≃ 42 GJ ≃ 40 million BTU
1 million barrels of oil equivalent = 5.8 trillion BTU
Crude oil – 139 000 BTU/gal = 38.8 MJ/liter
Gasoline – 125 000 Btu/U.S. gal = 34.9 MJ/liter
Diesel/heating oil – 139 000 BTU/U.S. gal = 38.8 MJ/liter
Ethanol – 84 400 BTU/U.S.gal = 23.6 MJ/liter
Natural gas – 1030 BTU/cf = 37 MJ/m^3
Coal – bituminous, ≃12 000 BTU/lb (28 MJ/kg)
Coal – sub-bituminous, ≃9000 BTU/lb (21 MJ/kg)

bert in 1956) make on U.S. production rates?

Problem 2. Given published estimates of world oil reserves and historical oil production data, calculate the approximate date of peak oil production.

Problem 3. Given world oil production patterns, that is, rates and cumulative production, what are the best estimates of ultimately recoverable world oil?

Data. The U.S. Department of Energy's Energy Information Administration maintains a database of energy information, including a record of yearly U.S. oil production from 1859 to the present.[9] Each year the company BP releases a review of world energy. In the 2006 edition[10] the estimate of world oil reserves is 1200.7 billion barrels of oil (note the precision). The U.S. Geological Survey (USGS) publishes estimates of cumulative oil production, oil reserves, and of ultimately recoverable reserves (URR). Their most recent mean value for the remaining possibly recoverable oil is 2628 billion barrels,[11] slightly more than twice that in the BP report. World oil consumption has grown at a rate of 1.6% per year over the past decade to about 80×10^6 barrels (80 MMbd) per day in 2004.[10] From 1885 to 1973 oil production worldwide increased at a constant rate of 7% per year.[8]

Answer 1(a). A relatively simple function to apply to the modeling of oil production is the Gaussian function, be it for one field, one country, or for the world as a whole.

$$P = Q_\infty A e^{-(Y - Y_{\mathrm{peak}})^2/2\sigma^2}, \tag{1}$$

where P is the oil production in a given year, Q_∞ is the URR, σ is the half-width of the production curve, and A is a normalization constant, $A = 1/\sigma\sqrt{2\pi}$. The time scale is given in years, with Y_{peak} the year of peak oil production. In Fig. 1 we show production data along with a Gaussian curve that characterizes the Energy Information Administration data for the history of oil production in the continental U.S. We can use a spreadsheet to plot the actual production data and corresponding Gaussian fits. Bartlett has analyzed the sensitivity of the fitting of production in the U.S. to Gaussians with differing parameters, and has extended this analysis to world oil production.[12]

It is possible to consider other fitting functions, and even a simple linear increase followed by a linear decrease can give an adequate representation of U.S. oil production.[1] In any case, we see that a simple, continuous mathematical function adequately describes the trajectory of U.S. oil production.

Hubbert used a more complicated mathematical formulation that also has a more useful physical interpretation. The logistic or Verhulst function is often used to describe growth in a system subject to a finite capacity or resource. The mathematical form of the logistic equation is given by

$$\frac{dQ}{dt} = bQ\left(1 - \frac{Q}{Q_\infty}\right), \tag{2}$$

where Q_∞ has the same meaning as before, Q is the cumulative production of oil, and dQ/dt is the rate of extraction. The initial (exponential) rate of growth of reserve production is described by the parameter b. The logistic equation can be given a plausible interpretation. The rate of production of a resource will initially increase exponentially, the ultimate limit to the resource being at first unimportant. As the cumulative production becomes a significant fraction of the ultimate reserve, extraction becomes more difficult, and the rate of extraction decreases. Because there is an ultimate limit to the amount of oil in the ground, the rate of production will eventually go to zero. The solution to Eq. (2) is given by

$$Q(t) = \frac{Q_\infty}{1 + \left[\dfrac{Q_\infty - Q(0)}{Q(0)}\right]e^{-bt}} = \frac{Q_\infty}{1 + ae^{-bt}}. \tag{3}$$

Note that there are three undetermined parameters that can in principle be found by comparison with actual data. In reality, the problem is not so simple, especially because eco-

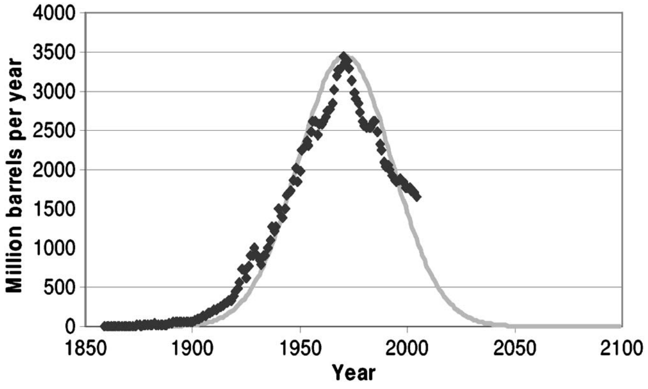

Fig. 1. Oil production and Gaussian fit in thousands of barrels per day. Data are from the U.S. Energy Information Administration (EIA); (Ref. 9) the Gaussian curve has parameters $Y_{\mathrm{peak}} = 1971$, $Q_\infty = 190$ Gb (1 Gb = 10^9 barrels of oil), and $\sigma = 22$ years. The data shown here represent crude oil production from the continental U.S. only, and include no natural gas liquids or oil from nonconventional sources.

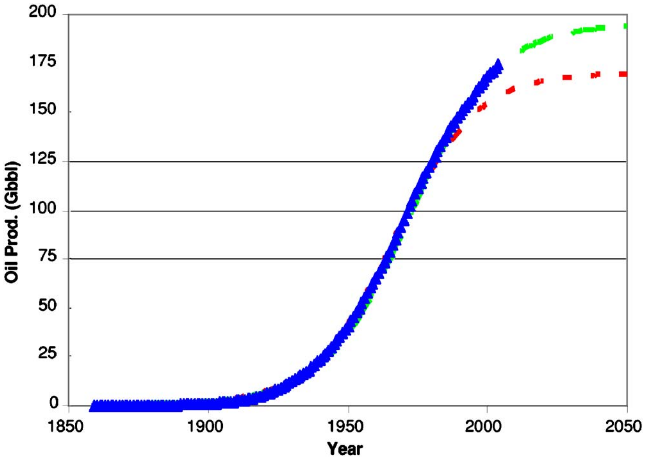

Fig. 2. Cumulative U.S. oil production and predictions in billions of barrels. The two logistic curves are based on predictions by Hubbert (Ref. 8), and from current trends. The ultimately recoverable reserves are ≈195 billion barrels.

nomic and political factors in the 1970s and 1980s led to a noticeable readjustment to trends in world oil production. The data for cumulative oil production in the continental U.S. along with two logistic curves are shown in Fig. 2. The lower curve corresponds to the parameters found by Hubbert[8] ($Q_\infty=170$, $b=0.069$, $a=1500$), and the upper curve is a fit using additional data for the past 25 years since Hubbert's paper ($Q_\infty=195$, $b=0.065$, $a=1500$). Hubbert predicted an ultimately recoverable reserve of about 170 Gb (where $\text{Gb}\equiv 10^9$ barrels) for the continental U.S.; it now appears that the trend will lead to an amount closer to 195 Gb. However, Hubbert did not consider off-shore deep-water oil or some of the enhanced oil-recovery techniques that have been applied since. Alaskan North Slope oil is not included here, because this resource was not part of Hubbert's initial calculation. One argument used against the concept of "peak oil" is that we will always find another source of oil or replacement energy when the economic and technological conditions are ripe. However, as we shall see, even these additional discoveries did not alter the fact that total U.S. production has never exceeded the 1970 peak.

A second point is that in the early, exponential growth stages of resource production, it is very difficult to determine the final trajectory of the production curve based on the logistic (or any other) model. It is only when the limiting factors become important that the two curves shown in Fig. 2 separate.

Answer 1(b). A complementary way of using the logistic equation is to plot current production as a fraction of cumulative production, taken as a function of the cumulative production itself. The production rate P is given by $P=dQ/dt$ and

$$P/Q = b - \frac{b}{Q_\infty}Q. \tag{4}$$

A plot of P/Q vs Q yields a curve that, after some initial noise, settles down to a fairly linear form. The x-intercept is the ultimate recoverable reserve, Q_∞. The straight line drawn on the curve (as a guide to the eye) in Fig. 3 leads to an ultimately recoverable reserve of about 200 Gb. We have also circled the point at which U.S. oil production actually peaked.

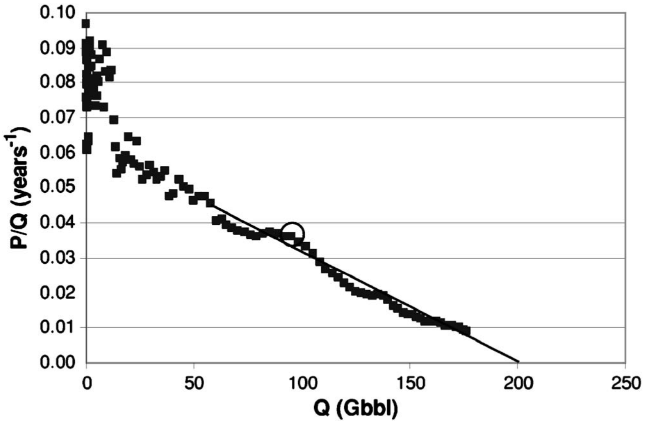

Fig. 3. The Hubbert linearization, a plot of P/Q vs Q (cumulative continental U.S. oil production). From the linear portion of the curve we can extrapolate to find the ultimately recoverable reserves, the point when production drops to zero.

Answer 1(c). Starting in the late 1970s, oil from Alaska became an important part of the U.S. production mix. The Alaskan North Slope represents one of the largest new oil discoveries of the past several decades, and therefore can be expected to play a large role in the shape of the U.S. production curve. Using data from the Energy Information Administration, we plot in Fig. 4 both the production from the continental U.S. and that of Alaska. The key point is that, although Alaskan oil is a significant fraction of total U.S. production, it did not provide enough additional oil to change the date of the overall production peak. Instead, Alaskan oil contributed a secondary peak to overall U.S. production, demonstrating that a single oil province can make a large difference in the production of a given country. In addition, the shape of production curves for the country as a whole does not have to follow the simple proposed relations because production is a sum of curves for individual oil fields.

Answer 2. The first set of examples using data for U.S. oil production serves as a background against which to evaluate the usefulness of the same techniques for predicting the pos-

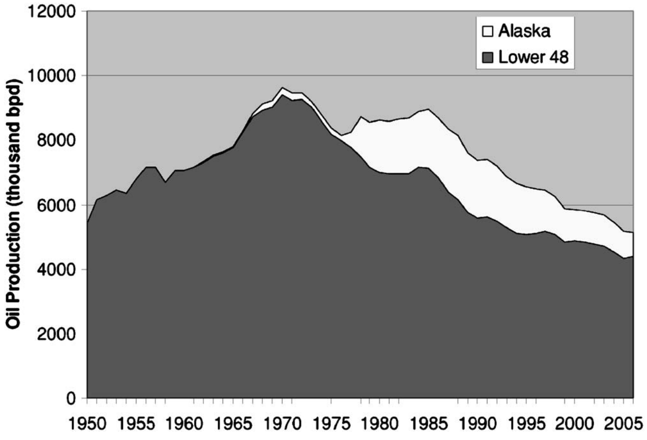

Fig. 4. Plot of combined continental U.S. and Alaska production in thousands of barrels per day. Alaskan production, although significant, has not been enough to reverse the overall decrease in production since 1970.

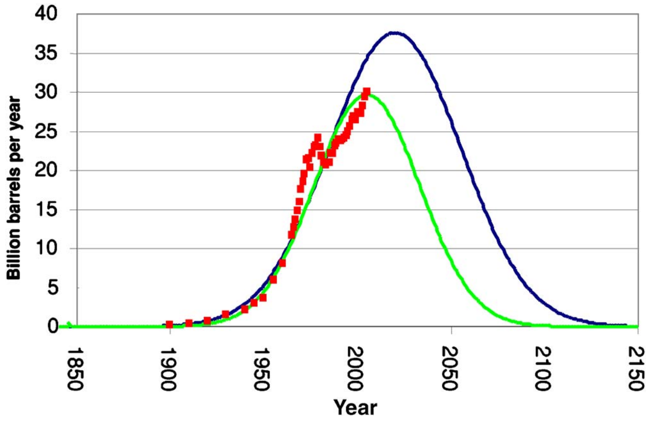

Fig. 5. World oil production and predictions in billions of barrels per year. The data points are actual world oil production. The two Gaussian curves are based on predictions by BP (smaller curve, URR of ≈2 trillion barrels) and the United States Geological Survey (larger area curve, 1998 estimate of ultimately recoverable reserves equal to ≈3 trillion barrels).

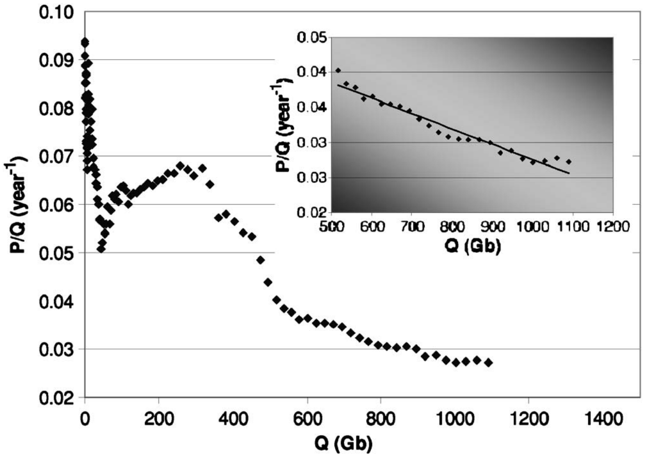

Fig. 6. Hubbert linearization for world oil production. A fit to the linear portion of the curve can be used to find the ultimately recoverable reserves, the *x*-intercept. The result is $Q_\infty = 2250 \pm 100$ Gb.

sible trajectory of world oil production. We can again use a spreadsheet to plot the actual production data and Gaussian curves with appropriate widths, maximum values, and total area such that agreement is reached (roughly) between the BP and USGS predictions for total production plus reserves and past history of oil production. Because it is more difficult to find a time-series record of world oil production for dates earlier than the BP data (before 1965), we use a trick to approximate the production. From approximately 1865 to 1973, oil production increased very nearly exponentially at a growth rate of 7% per year. In our model we use the exponential function to fit the data.

As shown in Fig. 5, the estimate for perhaps the most important unknown quantity, the year of maximum world oil production, does not vary much (BP: 2005, peak production 30 Gb/yr; USGS: 2020, peak production 35 Gb/yr). As was pointed out by Bartlett,[12] at current rates of oil use, for every billion barrels of recoverable oil discovered, the date of peak oil is moved back by approximately 5.5 days. New discoveries over the course of the past decade or so have been at the rate of less than 10 Gb/yr. The BP report does show slightly increasing reported reserves with time, with most of this increase coming from the reclassification of potential resources to actual reserves. The USGS value for remaining reserves might be considered as an upper limit for conventional oil, given that it relies on 1998 predictions of new oil discoveries occurring at a rate several times those actually seen in recent years.

Answer 3. The main problem with the estimates that we just found for the peak date is that, as long as we are on the "front side" of the curve, it is extremely difficult to clearly project the ultimate shape of the production curve given the fluctuations in oil production due to political and economic disruptions. It would be useful to have another method that could help more clearly indicate the ultimately recoverable reserve. As shown for the U.S., the Hubbert linearization technique provides a possibility. In Fig. 6 we show a plot of P/Q vs Q for world oil production, with an inset showing the region of the curve for which a linear regression was used to help extrapolate to the URR. The result is $Q_\infty = 2250 \pm 100$ Gb, which roughly agrees with what would be inferred from the BP data (≈2300 Gb), but is significantly lower than the USGS projection for URR (≈3700 Gb). However, this technique does not provide us with more precise output information than gained by fitting the production curve, because in both cases the starting point is the logistic equation.

Hafemeister[1] used the linear approximation to estimate the peak in world oil production, given optimistic and pessimistic values for recoverable reserves of 2100 and 1350 Gb, respectively. The corresponding peak dates he found were 2004 and 1993. These 30-year-old predictions, especially that of the optimistic case, seem remarkably relevant today.

To close out this section we comment on the intersection of science and public policy. It is inherently difficult to obtain sound, objective information about oil reserves and resources, a problem compounded by the secrecy with which these data are surrounded by oil-producing countries. Perhaps the best way to make an assessment of predictions about peak oil is to follow a given set of predictions for some time and see how well they match with actual data. It is also clear that economics will play a role in spurring oil production, a topic we will address later.

In 1999 Duncan and Youngquist[13] made 42 country-by-country predictions for oil peaking dates and maximum production amounts. The 42 countries chosen by the authors represent 98% of world oil production. The authors arrive at a predicted peak world production date of 2007, at a production of 30.6 Gb in that year. Their work is interesting in that we now have several years' worth of additional data to compare to their predictions. Of those countries, 14 had already reached peak production prior to 1997, and nine others were predicted to reach peak production after 2006. Therefore, 19 countries were predicted to experience a maximum in production between 1998 and 2006: 14 countries apparently did reach a peak in production, and seven of these countries do so somewhat earlier than predicted. At least six countries have either been at a production plateau for several years, or have been politically unstable so that production has varied wildly.

One topic that we have not yet addressed is that of nonconventional oil. This term can take on a variety of meanings, ranging from deep-water oil in the Gulf of Mexico to oil from the Arctic and other more exotic sources. If we consider the two most-discussed resources in this category, tar sands and shale oil, there exist, in principle, very large amounts of oil to be recovered. We will consider the feasibility of large-scale production of these resources in the following. It is not necessarily the reserves or resources that are most important, but the rate at which these can be produced, as well as the net energy gain from production. Even optimistic industry estimates predict that these nonconventional sources will play a small role for the next few decades.

In summary, the best estimates of the ultimately recoverable reserve of world oil lie between 2000 and 3000 Gb, whereas total consumption to date is approximately 1000 Gb. The date of peak oil production based on these estimates is likely to be between 2005 and 2020. Oil reserves are often quoted in the media in terms of the number of years left, based on current production levels. For example, a remaining reserve of 1500 Gb at a current production of 30 Gb per year leads to the oft-heard statement that we have 50 years of oil remaining. From the previous examples it should be clear that a more relevant number is the date of peak production, after which demand for oil will be, all else being equal, greater than the amount that can be produced. This geological peak is not to be confused with the economic mismatch between global demand for oil and the current supply capacity, a situation that may arise with or without the geological peak.

We now turn to one of the critical uses for petroleum, the transportation sector, which, at least in the U.S., depends almost entirely on petroleum.

III. DRIVING HABITS, FUEL EFFICIENCY, AND CONSERVATION

About two-thirds of oil consumption in the U.S. is currently due to the transportation sector.[14] It seems reasonable to assume that potential changes in the transportation sector will also play a large role in reducing the need for oil in the future. Even if peak oil production is several years in the future, there are economic ramifications (chiefly in the form of increased oil prices) if world oil demand increases more quickly than supply infrastructure changes can be made.

There are three broad possibilities for reducing transportation fuel demand (chiefly gasoline, but also diesel fuel). We can change current driving habits to use less fuel, develop new technologies that use fuel more efficiently, or switch to alternative fuels. An interesting analysis of the second case is given by Hirsch.[15] We now consider several possible pathways for reducing gasoline demand. A key point in light of the peak oil scenarios discussed in Sec. II is the time scales involved. If oil production is nearing a peak, reduction of fuel use must occur fairly rapidly even without growth in demand.

Problem 4. If we consider a savings of 1 million barrels per day of oil, equivalent to 5% of our current consumption, to be a significant contribution to reducing dependence on fossil fuels, how many fewer miles per day should an average United States citizen drive if the country as a whole is to reach this goal?

Problem 5. What would be the savings in gallons per year consumed by automobiles if highway speeds were 60 mph instead of 70 mph?

Problem 6. How much fuel could be saved by increasing car-pooling rates by 100%?

Problem 7. How much fuel could be saved by cutting the average number of shopping trips in half?

Table II. Light vehicle usage and mileage for the U.S. fleet. Miles/yr and mileage are averages for the current U.S. fleet.

Vehicle	Number	Miles/yr	Mileage	Gas cons.
Car	136×10^6	12 200	22.1 mpg	7.5×10^{10} gal
Light truck	85×10^6	11 400	17.6 mpg	5.5×10^{10} gal

Problem 8. Make a simple model of the gasoline savings to be gained by continually replacing the current fleet of automobiles by models with twice the current Corporate Average Fuel Economy standard fleet average efficiency (that is, hybrid gasoline-electric automobiles or the equivalent). Assume as a simplifying approximation that all light-truck owners begin trading in their vehicles for efficient automobiles, and that the automobile industry can increase production of such autos from current rates by 25% per year. How do these scenarios compare to the gasoline saved by decreasing the miles driven by 2% per year? Do all your calculations up to the year 2025, the year to which the Energy Information Administration makes its forecasts.

Data. We first present some data from the annual Transportation Energy Data Book[14] in Table II. Additional gasoline and diesel fuel consumption comes from buses, heavy trucks, and other vehicles, none of which is considered here. For convenience various data will be given to two or three digits, but the numbers given should not be taken as indicative of the true number of significant figures.

From Ref. 14 we find that the U.S. consumed 20 million barrels per day (MMbd) of oil in 2004, with 66% or 13.2 MMbd going for transportation. As typically refined in the U.S., 42 gallon barrels of crude oil yield 19 gallons of gasoline,[16] with the rest divided among products such as diesel fuel, home heating oil, kerosene, and others. In what follows, we will equate 1 million barrels of oil to 19 million gallons of gasoline, assuming that consumption of the other products will also be decreased.

An average trip to work is 12.1 miles, with work-related driving accounting for 27% of total miles driven; about 13% of 111 million commuters car-pool to work. Shopping trips account for 21.1% of all trips and 14.5% of all vehicle miles traveled, with an average trip being 6.7 miles.[14]

For the model year 1997 cars that were tested, the mileage increases by about 17% from 26.8 to 31.4 mpg by reducing the driving speed from 70 to 60 mph. (Maximum efficiency is for travel at 50–55 mph.) For 1984 cars, the mileage goes from 22.5 to 27.6 mpg for the same speed decrease, an improvement of 23%.[14]

Answer 4. To save 1 MMbd of crude oil imports or production, it would be necessary to burn 19×10^6 fewer gallons of gasoline each day, assuming that uses for the other products of refining a barrel of oil can be reduced commensurately. We can approximate the data for driving to obtain an estimate. Assume that an average vehicle gets 20 mpg and drives 12 000 miles per year. Given the yearly driving per vehicle, the daily distance driven is 33 miles. With this simplification we see that saving 1 MMbd out of 13.2 MMbd current consumption of transportation is equivalent to driving (1 MMbpd/13.2 MMbpd) × 33 miles per day = 2.5 miles per day less. For comparison, it has been estimated that one-half to two-thirds of driving trips in the U.S. are discretionary (a matter of definition), but if 10% of miles driven could be avoided, the 1 MMbd (19 million gallons of gasoline/day, or 7×10^9 gallons/yr) goal would be met.

Answer 5. Savings due to speed limit reductions are based on data for automobiles published in Ref. 14. From this source we can only guess at the percentage of miles traveled at highway speeds; for our purposes, we use 20% as a reasonable estimate. For $0.2\times2.6\times10^{12}$ miles at an average mileage for cars of about 24 mpg (between the values for the 1984 and 1997 cars, as stated in the section on mileage and speed in Ref. 14), gasoline usage is 2.2×10^{10} gal/yr. At an increased mileage of 30 mpg (between the 1984 and 1997 data), we find gasoline consumption of 1.7×10^{10} gal/yr, for a savings of 5×10^9 gal/yr (14×10^6 gallons/day), equivalent to 740 000 bbl/d (using the refining yield mentioned previously).

Answer 6. Savings due to increased rates of car-pooling can be found by using the fact that 9.7×10^7 people ride alone and 1.4×10^7 people car-pool,[14] accounting for $(0.27)\times(2.6\times10^{12})$ miles. Doubling the car-pooling number to 28.8 million people, and using the same average trip, 12.1 miles, and an average mileage of 20 mpg means that there would be a daily reduction of $(14.4\times10^6)\times(12.1\text{ miles})/(20\text{ mpg})=8.7\times10^6$ gallons/day (3.2×10^9 gallons/yr), which is the refined equivalent of about 460 000 barrels of oil per day.

Answer 7. Because shopping accounts for 14.5% of vehicle miles traveled, we can use an estimated average gasoline mileage of 20 mpg to find $(0.145)\times(2.6\times10^{12}\text{ miles/yr})/(20\text{ mpg})=1.9\times10^{10}$ gallons/yr. Cutting the number of trips in half would save $\approx10^{10}$ gallons/yr or 2.7×10^7 gallons of gasoline each day, the equivalent of 1.4×10^6 barrels of oil each day.

Taken together, these four scenarios represent a total savings of approximately 75 million gallons of gasoline per day (27 billion gallons each year).

Answer 8. We use a simple spreadsheet (available from the authors) to calculate changes in gasoline consumption based on the previous assumptions. In recent years, the automobile and light vehicle fleet in the U.S. has grown by about 1.5%/yr and an average passenger car travels 12 200 mi/yr and the average light truck travels about 11 300 mi/yr. If we keep these numbers constant, total gasoline use in the country slowly decreases over time due to newer, slightly more efficient autos replacing older, less efficient models ("business-as-usual" scenario). This scenario is optimistic, because actual gasoline usage has been rising by 2%/yr for the past decade, and has continued to rise even in the face of higher gasoline prices over the past 2 years.[14]

We plot in Fig. 7 the cumulative amount of gasoline saved under different assumptions. We include the sum of the savings from the scenarios discussed in Problems 4–7 (labeled "Habits"), taken with respect to the business as usual case. A change in the number of miles driven per year alone, and continued over a long period of time ("Drive 2% Less per Year"), also leads to a significant decrease in total gasoline usage, approximately 12.5 billion gallons per year.

In contrast, even a massive introduction of hybrid vehicles at a sustained rate of growth of 25%/yr takes several years to have a large effect on overall gasoline usage ("Hybrid Intensive"), as illustrated in Fig. 7. Not until near the end of our time window do yearly gasoline usage reductions from hybrid (or other high mileage) vehicles begin to catch up to the efficiencies achieved by simply driving less. For this scenario we have assumed that hybrids initially replace lower mileage trucks only. As production increases, average cars are also replaced by hybrids as well, until by about 2020 all new vehicle production is in the form of hybrids. It is almost certainly not realistic to think that production of 50 mpg cars will grow at 25%/yr for 20 years, such that finally all vehicles produced will have mileage at that level.

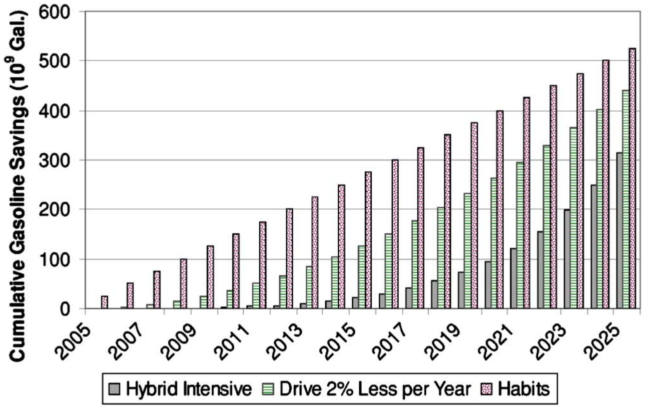

Fig. 7. Cumulative gasoline savings over the next 20 years for three scenarios: a hybrid-auto intensive future, a combination of driving-habit changes, and a reduction in miles driven per year. The scenarios are described in the text; the savings are taken with respect to a business-as-usual scenario.

It is clear that the quickest alternative for short-term gasoline savings is in the form of conservation. The lesson is that personal behavior changes can have a significant, immediate effect, whereas technological changes to an infrastructure as large and long-lived as that of automobiles require a long lead time. In Ref. 14 we find that the average lifetime of an automobile is about 15 years, and the average age of cars on the road is about 9 years. These facts illustrate the time scales inherent in making technological efficiency changes.

Two further points bear mentioning. Predictions for the rate of decrease in the oil supply for the case of world peak-oil production are in the range of $3\%-5\%/\text{yr}$; the 2% decrease in driving each year assumed in our scenario could therefore only be a part of the action taken to reduce energy use if peak oil were imminent and of such severity. Second, a common phenomenon known in economics as Jevons' paradox[17] might mitigate further against the savings found by the introduction of hybrid technology. As noted by the 19th century English economist William Stanley Jevons, as technologies are introduced that use a natural resource more efficiently, we will very likely more than compensate for the increase in efficiency by finding new uses for the resource. It is not clear how far this effect will play a role in the case of possible peak oil production.

In Refs. 1 and 2 Hafemeister considered the possible savings by increasing mileage standards for automobiles (13 mpg average in 1974) and by changing personal driving habits. Progress was initially made in automobile mileage after the introduction of the Corporate Average Fuel Economy standards in 1975. Since 1990 improvements in mileage have stalled, and because of the increase in low-mileage pickup trucks, minivans, and sport utility vehicles, overall mileage in the U.S. fleet has been decreasing since the late 1980s.

IV. TRANSPORTATION MODES

Total U.S. energy use for transportation in 2004 was 26.9 quadrillion BTU, the energy equivalent of 4.6×10^9 barrels of oil. Of this energy, 61.4% was used by light vehicles, 8.4% was due to air travel (mostly passenger), and only 0.4% was due to passenger rail transport. We now investigate a few of the issues surrounding the energy use for different types of transportation.

Problem 9. Compare the energy necessary for building a new automobile with the energy used to drive the car for 150 000 miles.

Problem 10. Compare the energy intensity for three modes of travel: automobile, train, and airplane. Give your answers in BTU/passenger-mile.

Problem 11. How many months of automobile gasoline energy does a single person's share of one round-trip flight to Europe represent?

Problem 12. Compare the estimated cost in energy and in time for driving and flying for a 500 mile trip.

Data. The embodied energy in an automobile can be estimated using a life-cycle analysis approach.[18] From Ref. 18 the embodied energy in a manufactured automobile is approximately 10^8 BTU, depending on the car model. Fuel economy for new cars averages 29 mpg.[14] Although this number seems generous in light of estimates made by other agencies, which are as much as 15% lower,[19] we will use it in what follows.

In Ref. 14, Tables 9.2 and 9.14, we find energy intensity for domestic air and rail travel to be 3800 BTU/passenger-mile and 2800 Btu/passenger-mile, respectively, and that the total intercity air travel energy consumption is 2.7×10^{15} BTU for 7.1×10^{11} passenger-miles in 2000. From the same source we find that roughly 27% of all vehicle-miles traveled are for work purposes and that vehicle occupancy rates are 1.1 persons/vehicle for work-related trips and roughly 1.8 persons/vehicle for other trips. Total gasoline and diesel energy use for light vehicles is 1.6×10^{16} BTU/yr.

Answer 9. For an average new car with gasoline mileage of 29 mpg,[14] the lifetime consumption will be approximately

$$\frac{150\,000\text{ miles}}{29\text{ miles/gallon}}\times125\,000\text{ BTU/gal}=650\times10^6\text{ BTU}. \tag{5}$$

Compared to the energy embodied in manufacturing the car, $\approx100\times10^6$ BTU, the energy consumed during its lifetime use is clearly dominant. It is interesting to consider the consequences of building automobiles such as hybrid electric vehicles that may be twice as efficient, but use larger quantities of energy-intensive materials such as copper and aluminum. At some point the embodied energy becomes a significant fraction of the total lifetime energy consumption. Hafemeister[2] considered some of these issues in more detail. The same can be argued for energy-efficient buildings: for buildings that use very little energy for heating or electricity, the embodied energy in the building materials becomes an increasingly important consideration.

Answer 10. For air and rail travel we have a direct comparison that can be made from the data. For automobiles we can take the total energy, the total number of miles driven, and the average occupancy to find

$$\frac{1.6\times10^{16}\text{ BTU}}{(1.5\text{ passengers/vehicle})(2.8\times10^{12}\text{vehicle-miles})}=\frac{3800\text{ BTU}}{\text{passenger-mile}}, \tag{6}$$

where we have used an estimated overall average of 1.5 passengers/vehicle.

Answer 11. A round-trip flight to Europe from the Midwest is approximately 10 000 miles. At an energy intensity of 3800 BTU/passenger-mile, such a trip represents an energy use of approximately 3.8×10^7 BTU, or 3.8×10^7 BTU/125 000 BTU/gal=300 gal of gasoline. (The volumetric energy content of jet fuel is roughly the same as gasoline.) We compare this use to yearly travel of 12 000 miles at 20 mpg, or 600 gal of gasoline. We see that a single round-trip flight "costs" about 6 months worth of gasoline. For a family of four, we estimate that the 1200 gallons used flying is the equivalent of about 2 years' worth of driving.

Answer 12. For a 500 mile trip, an average light vehicle will use 500 miles/20 mpg=25 gallons of gasoline, or 3×10^6 BTU (for as many people as we wish to put in the car). A flight of the same distance uses (500 miles) ×(3800 BTU/passenger-mile) for each passenger, or 1.9×10^6 BTU (for each passenger). The former might be seen to overstate the case, because the average mileage of newer cars is closer to 29 mpg, whereas the latter underestimates the fuel used because proportionately more fuel is used in starting and landing on a short flight than on a long flight. On the other hand, airplanes also carry nonbaggage cargo, thus affecting the passenger energy efficiency.

We can estimate the time spent traveling by assuming a door-to-door trip at mostly highway speeds to take 500 miles/60 mph=8.3 h, which we round to 9 h to account for slower periods of travel. For the flight, we estimate 0.5 h for the trip to a nearby airport, 1.5 h waiting time (recommended arrival time before the flight), 1.5 h flight, and 1 h to disembark, claim luggage, and travel to the final destination, for a total of 4.5 h. Roughly speaking, the short flight uses twice the energy of driving and takes half the time.

These numbers should be used with caution, due to their great uncertainties. A history of U.S. transportation energy efficiency[20] attempts to sort out some of these issues. To a first approximation, it is found that energy intensities for all modes of transportation are equal, at about 3500 BTU/passenger-mile, with certainties of $\approx\pm500$ BTU/passenger-mile (estimated from various calculations).

In Ref. 1, Hafemeister looked at similar scenarios to those presented in this section and refers to the possibility of a 50% savings in transportation fuel consumption achievable by habit changes. At the time (using numbers from 1970) transportation energy use was 1.65×10^{16} BTU; as noted, current consumption is 2.64×10^{16} BTU. The population of the United States has grown over the same time interval from approximately 200 million to 300 million; therefore, per capita annual transportation energy has increased from 8.3×10^7 to 8.8×10^7 BTU/person.

V. ALTERNATIVE FUELS

There have been many suggested fossil-fuel substitutes for conventional petroleum and natural gas. Examples are shale oil, tar sands, and gas hydrates, all of which are believed to exist in resources totaling many times the amounts currently published for conventional oil and gas resources. Numbers commonly accepted for these resources are 3600 billion barrels of oil in Canadian tar sands and Venezuelan heavy oil, 1800 billion barrels of oil shale in the U.S., and approximately an equal amount elsewhere in the world,[21] and 600–6000 billion barrels of oil equivalent (10^{14}–10^{15} m^3) in methane hydrates in the ocean.[22] These numbers are to be compared to the approximately 1200 billion barrels of oil, along with 179 trillion cubic meters of natural gas (1100 billion barrels of oil equivalent), thought to be proven and recoverable under projected economic conditions.[10]

These numbers might seem to make the whole discussion of this paper moot, except for three cautions. First, the actual recoverable amounts of these nonconventional resources will vary greatly depending on economic factors. In general, the economically recoverable reserves are a small fraction of the estimated totals in place. Second, the crucial variable for thinking about peak oil production is, in the end, the rate of production and not the total reserve amount. For example, even in an optimistic scenario the production of oil from Canadian tar sands is expected to increase by at most ≈ 1 MMbd every 5 years, reaching an output of 5 MMbd in 2030 (Ref. 23) (if Canadian natural gas production, now in decline, can meet the demand). Finally, although it is clear that an energy input is necessary to extract fossil fuel resources, this input energy has usually been neglected because the ratio of output to input energies has been relatively high. For conventional oil and gas resources the ratio of output to input energies is high enough that the latter is of little importance. For nonconventional tar sands oil, the energy return on energy invested (EROEI) might be as little as 2:1 (perhaps as high as 5:1; it is difficult to find well-documented numbers), compared to 20:1 for conventional oil and natural gas.[24] Thus, the net energy available to perform other useful work is significantly less than it is for a high-EROEI resource. According to Ref. 24 the EROEI of oil and gas extraction has declined from a value of 100:1 in 1930. The ratio is not constant, and is an indicator that extraction of fossil fuels is becoming more difficult.

A second category of fossil-fuel substitutes are those derived from biomass. Currently the most commonly discussed source of biofuel in the U.S. is ethanol derived from corn. In Brazil there has been much success making ethanol from sugar cane, and in Germany various forms of biodiesel are fairly common. Again, several questions arise when considering these sources of liquid fuel energy. First, the EROEI question is acute, although controversial,[25–27] and even in a best-case scenario, corn-to-ethanol provides an energy return ratio of about 1.3:1. Second, if the whole energy conversion process is considered, ethanol production plus combustion result in only about a 15% decrease in overall carbon dioxide emissions.[27] Third, there is a serious ethical question to consider if we convert what is essentially a food and animal feed crop into fuel for vehicles.

Another possible source of substitutes for fossil fuels is found in renewable resources such as wind and solar energy, the former for electricity generation, the latter for both electricity and thermal energy. At present, these sources make up $\approx 0.18\%$ and 0.06%, respectively, of U.S. energy consumption.[28] Currently, the largest contribution to the use of renewable energy in the U.S. is due to hydroelectric power generation; however, this option leaves little room for future large-scale expansion.

In the following problems we investigate various energy scenarios. It is not our intention to make prognostications about which scenarios might be most likely, but taken together, they give a sense of the options available in the event of a future decrease in the availability of oil and/or natural gas. The energy scenarios are implemented using a spreadsheet and make assumptions for each energy pathway that are roughly consistent with what can be found in the open literature and from projections of companies in the energy industry.

Problem 13. If the United States were to replace all transportation fuel with ethanol distilled from corn, how much land would be required? How does this result compare to the total amount of agricultural land in the U.S.? (Nobody would suggest that such an extreme substitution could take place.)

Problem 14. Considering the EROEI of ethanol production from corn, and assuming that 25% of future gasoline demand could be met by ethanol, what is the energy equivalent in barrels of oil production per day that will be required for transportation by 2025?

Problem 15. If the U.S. were to move heavily into wind energy and photovoltaics, what annual growth rate would be necessary for these sources to deliver 50% of electrical demand in the country by 2050? For the world? Assume equal shares for wind and solar electricity in 2050.

Problem 16. Given current estimates for the future contribution of nonconventional oil sources and for conventional oil and natural gas shortfalls, model the future energy supply for the U.S. under different plausible scenarios.

Data. Total planted cropland in the U.S. is about 320 million acres. Corn production represents about 25% of this cropland, with an average yield of 140 bushels/acre.[29] This yield is increasing over time at about 2%/yr. Conversion to ethanol yields 2.6 gal/bushel of corn. The energy density of ethanol is approximately 63% that of gasoline, 80 000 BTU/gal compared to 125 000 BTU/gal. Energy use for light vehicle transportation is 16.2×10^{15} BTU (16 quads), and is growing at 2%/yr.[14]

Total electricity consumption for the U.S. (currently 4.2×10^{12} kWh or 4200 TWh) has grown at about 2%/yr over the last 10 years and world net electricity consumption (currently 18 200 TWh) has grown at 3%/yr.[10,30] From 1998 to 2004, the use of wind in the U.S. as an energy source grew at a rate of 25%/yr from 0.031 to 0.14 quads (4.1×10^{10} kWh), while solar photovoltaic capacity has grown by $\simeq 18\%$/yr.[28,31] Currently (as of 2004), approximately 0.2×10^{10} kWh of electricity was generated from photovoltaics.[31,32] Worldwide, solar electric growth has been at a rate of 6.5%/yr (2002 electricity generation was 1 TWh) and wind energy has grown at 23%/yr (2002 electricity generation was 11 TWh).[33]

Answer 13. Because light vehicle transportation energy use is currently 16.2 quads per year, to replace this use fully with ethanol from corn as currently produced would require $16.2 \times 10^{15}\ \mathrm{BTU} = 8 \times 10^4 \mathrm{Btu/gal} \times 2.6 \mathrm{gal/bushel} \times 140\ \mathrm{bushels\ /acre} \times (\text{number of acres})$. The total of 556 million acres of land is significantly more than the total planted cropland in the U.S. Several caveats are in order. Automobile engines can be tuned to higher compression ratios for use with ethanol, thus negating part of the energy density disadvantage. Second, we would hope that a large-scale retooling of the transportation sector would also include a significant increase in mileage for automobiles. In any case, it is impractical to rely on this alternative source of energy for anything more than a small fraction of total transportation energy needs.

Answer 14. An EROEI of 1.5 implies a net energy "profit" of 0.5 units of energy for every unit of energy input. If transportation energy use is increasing by 2%/yr, consumption will be 24.2 quads by 2025. For ethanol to make up 25% of this energy we would need 6 quads of net energy; another 4 quads of energy is needed for the production of this ethanol, the energy equivalent of 2.1 MMbd of oil production. Note that we have not accounted for 75% of an increasing amount of transportation fuel, or 18 quads, the equivalent of 9.4 MMbd, an amount more than we currently use for light vehicle transportation. In the face of a peak in world oil production, it appears unlikely that continued large increases in ethanol production is a likely scenario.

From Answer 13 the required amount of corn-based ethanol requires 200 million acres of planted corn. Although corn yields are increasing at 2%/yr, it is inconceivable that this amount could be produced, even if all other uses of corn are eliminated. The net result is that ethanol produced from corn will only be a marginal part of the future energy picture. Once again, if the problem we face is one of insufficient liquid fuels, changing personal habits is the most energetically favorable solution.

Answer 15. If the current 2% annual increase continues in the U.S., electricity demand in 2050 will be $(3.7\times10^{12})\times\exp(0.02\times45)$ kWh$=9.1\times10^{12}$ kWh. We aim for solar and wind energy to generate 2.3×10^{12} kWh each. From the current production levels of 1.8×10^{10} and 3.2×10^{10} kWh we can calculate the annual rate of increase needed to achieve our goals. For photovoltaics we find the rate of increase to be 11%/yr, while for wind-generated electricity the increase is 9.5%/yr. These are both apparently within the realm of possible rates of increase.

For world electricity generation we similarly calculate the demand in 2050 to be 59 400 TWh, necessitating 15 000 TWh each of solar electric and wind energy. If we start from the 2002 numbers, the required rates of increase are found to be 21%/yr for solar and 16%/yr for wind. Both of these rates of increase are currently being achieved; the larger question is the sustainability of these rates of growth.

We note that the International Energy Agency (IEA) predictions for renewable energy growth are somewhat less than those that we just calculated,[33] and the projections are for the shorter time period 2002–2030. Over this time the IEA predicts growth rates of 11% for wind and 16% for solar electric generation. They also include other important categories for electricity generation that we have not considered here, such as biomass and waste, geothermal, and tidal or wave energy. These additional sources for adding to the renewable electricity generation portfolio allow somewhat greater optimism for substitution scenarios, as well as giving regionalized optimization possibilities.

Finally, we note that for the case of renewable energy electricity generation, each kWh of energy displaces approximately three times as much fossil fuel energy, because power plant efficiency is no longer an issue. This simple argument ignores the initial energy input needed to manufacture wind turbines and solar panels, as well as the increased efficiency available when waste heat from conventional power plants is utilized. A topic that we do not address here is that of end-use energy in contrast to primary energy consumption; when comparing fossil fuel energy use and electrical energy use, we must be careful to keep track of this distinction.

Closely related to the idea of EROEI for fossil fuels is the concept of life-cycle assessment when considering renewable energy technologies.[34] Manufacturing photovoltaic panels or wind turbines takes energy. Life-cycle assessment attempts to perform a cradle-to-grave analysis of the energy inputs (and greenhouse-gas emissions) for a given process. Although the results vary somewhat, a rough estimate is that the input energy for wind turbine electricity generation represents about 3% of the lifetime energy generated, equivalent to an EROEI of ≈ 30. For solar photovoltaics, the energy input is on the order of 8%–10% of the lifetime energy generation,[35] which is equivalent to an EROEI of $\approx 9:1$.

Answer 16. We discuss four scenarios for future energy production in the U.S. and briefly state the rationale for each scenario. After presenting an overview of the results of each, a summary will be given of the total energy production as a function of time for each scenario. It is clear that none of these scenarios will correctly describe the future course of energy use, but as a group they can help provide a sense of the magnitude of the problem to be faced if petroleum production reaches a worldwide peak by the end of the decade. In all of the scenarios we assume that both oil and natural gas reach a peak in consumption in 5 years. Although worldwide production of natural gas is estimated to peak approximately 20 years after oil, the situation in the U.S. is more critical. Both the number of wells drilled and the success rate of wells drilled in the past 5 years have increased; at the same time, U.S. proven reserves and production have both been flat or decreasing for most of the past 25 years. For all four scenarios we assume a decline rate of natural gas and oil availability of 4%/yr beginning in 2010, after growth rates of 0%/yr and 1%/yr, respectively. Hydroelectric power and geothermal energy are taken as constant, and except where noted, biomass as an energy source increases at 1%/yr.

The first scenario is a slight modification of current energy use practices. Solar energy does not increase and wind energy is predicted to grow at 10%/yr, roughly consistent with rates in the recent past, while nuclear power production and use of coal both increase at 1%/yr, again consistent with the recent past. The prognoses for an increase in production of shale oil and methane hydrates are based on industry, government, and private think-tank studies.[36] Shale oil production is assumed to begin commercially in 10 years and to have a yearly rate of production increase of 0.1 MMbd/yr, consistent with the prediction that, "Under high growth assumptions, an oil shale production level of 1 MMbd is probably more than 20 years in the future, and 3 MMbd is probably more than 30 years into the future."[36] From Fig. 8 we see that this scenario predicts a continued dominance of fossil fuels in the energy mix of the next three decades. Even at growth rates of 10%/yr for renewables such as solar and wind energy, the vanishingly small initial levels do not allow these technologies to make a significant contribution.

The second scenario, shown in Fig. 9, can be thought of as a "green" alternative to the business-as-usual model. There are three primary assumptions that go into this model: Solar and wind energy increase from current levels at a rate of 25%/yr for 30 years; nonconventional sources of petroleum products are assumed not to play a role, and decline rates of natural gas and oil production are 4%/yr as before. The as-

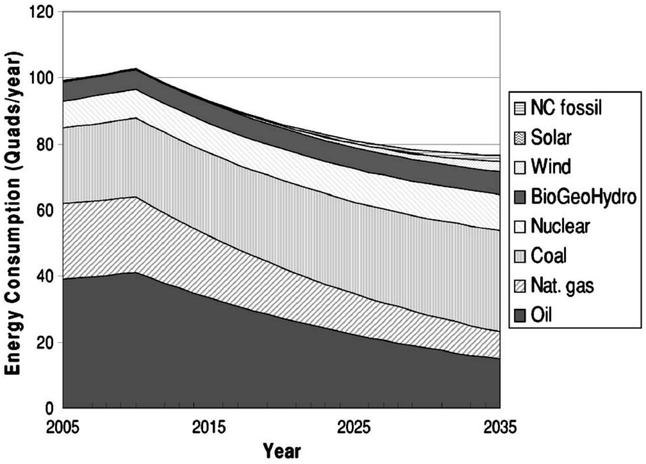

Fig. 8. The moderately changed business-as-usual energy future scenario. Solar energy is too small to see on the plot and wind energy grows at 10%/yr, while nuclear power and coal as energy sources grow at 1%/yr as is currently the case.

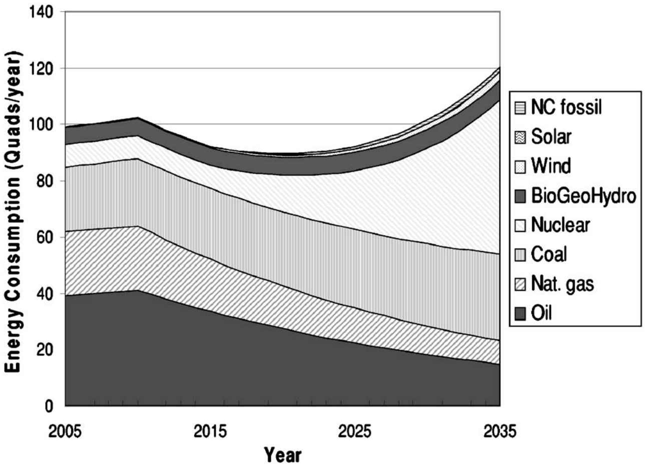

Fig. 10. The nuclear-supplemented fossil-fuel energy future scenario. Wind energy grows at 10%/yr and coal grows at 1%/yr, while nuclear power as an energy source increases at 10%/yr beginning in 10 years to allow for ramp-up. Solar is too small to be visible.

sumed growth in solar and wind energy implies nearly 100% renewable energy use by the end of the time period. Biomass use grows at 2%/yr.

With the larger growth rate for renewable energy sources, these begin to make a significant contribution to the total energy mix by the final decade of the projection time. There are clearly limits to this analysis, as symbolized by the exponential runaway in contributions from wind and solar energy during the final few years of the simulation time. Although we could be skeptical of the assumed growth rate of 25%, Germany has had a 33%/yr average rate of growth in production for wind energy, 40%/yr photovoltaic electricity, and 19%/yr for solar thermal energy production, all maintained for the past 10–15 years. Total primary energy consumption in Germany over the same time period remained constant, to within about 1%, so that the contribution to total energy use of these renewable sources is approximately 5% (compared to 0.2% in the U.S.).[37]

Our third scenario might be termed a nuclear-dominated future. The estimates for nonconventional petroleum products (shale oil and hydrates) are as in the first scenario, while wind energy grows at 10%/yr, again as in the first scenario. Nuclear power, after an initial delay of 10 years, begins to increase at 10%/yr. The delay might be justified by looking at the time it takes to have a nuclear power plant proposed, approved, and built (assuming that the latter happens at all). Because nuclear power already accounts for 20% of our electricity production, the growth rate of 10%/yr allows nuclear power to become the dominant energy source by 2035 in this scenario, as shown in Fig. 10. Nuclear power plants compete very favorably with other renewable energy sources with respect to life-cycle greenhouse gas emissions,[38] but nuclear fission relies on a nonrenewable resource. The possibilities presented by breeder reactors and/or nuclear fusion are not considered here.

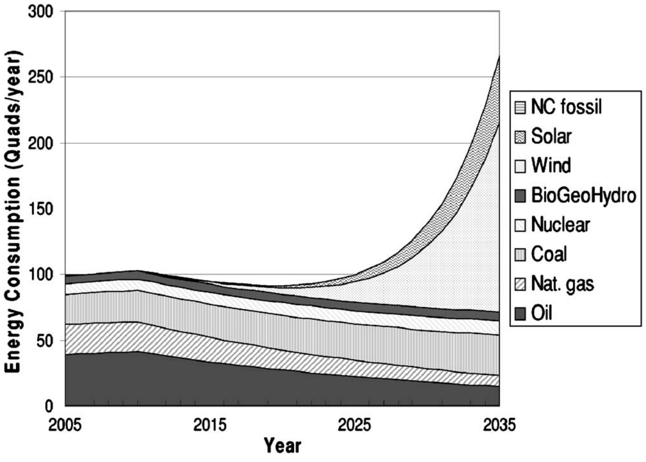

Fig. 9. The green energy future scenario. Solar and wind energy grow at 25%/yr, while nuclear power and coal as energy sources grow at 1%/yr as is currently the case. Finally, nonconventional oil and gas development are not pursued and therefore too small to be visible in the plot.

The final scenario we consider is a coal-dominated energy future. Assume for the sake of argument that nonconventional petroleum is impracticable at higher rates of increase, that nuclear is unacceptable, and that renewables do not increase any faster than the base case outlined in the first scenario, coal is plentiful enough and easy enough to use as a substitute for declining conventional oil and natural gas. These assumptions lead to the prediction shown in Fig. 11. At a growth rate of 5%/yr, coal-based energy relatively quickly comes to dominate the energy mix in the U.S.; air pollution and mitigation of CO_2 emissions become major issues under this scenario.

In our initial discussions of all four scenarios we concentrated on the relative contribution of each energy source toward the end of the 30-year time frame. A critically important result to consider from these models is that of the total energy supply due to all sources. Figure 12 shows the total energy supply as a function of time for the various scenarios, along with a projection of energy use based on the 1%/yr growth in consumption experienced in the past two decades. The key lesson seen here is the importance of fossil fuels to our total energy consumption, and that replacement of fossil fuels, or even a switch to a different mix of fuels, is a time-consuming and potentially costly process. When the peak in oil production does occur and U.S. supplies of natural gas become as difficult to replace as posited in these scenarios,

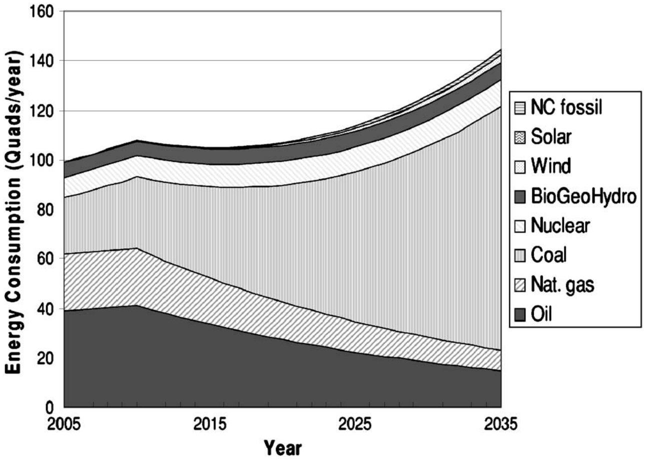

Fig. 11. The coal-enhanced fossil-fuel energy future. Coal consumption increases at a rate of 5%/yr. Wind energy grows at 10%/yr, while nuclear power grows at 1%/yr as is currently the case. Solar energy is too little to be visible.

only in the green and coal scenarios (very optimistic, given recent past history and worries about environmental damage, respectively) does total energy supply by the year 2035 equal that which is projected based on the energy consumption increases of the recent past.

The results shown in Fig. 12, more than any other single piece of information, encapsulate the arguments of the "peak oil" community. There is no danger of oil suddenly "running out." After the peak, production will begin a long irreversible decline, and it will be difficult to find substitutes on short times scales that will allow the U.S. to use as much total energy as we do currently, let alone continuing to increase energy use. For the green, nuclear, and coal scenarios, we might predict a society in 2035 that uses about as much energy as we currently project will be necessary based on continuous 1%/yr growth. However, there will be a significant time interval, except in the coal-intense future, during which energy use will be constrained. (The assumptions made in generating these results are only rough guidelines.)

Another scenario has been added to this summary, labeled "conserve" in Fig. 12. For this curve it was assumed that total energy use in the U.S. decreases by 3% per year for the next 30 years. Thus, energy use will be cut in half by about 2028; given projections for continued population growth in the U.S. during that time interval, the decrease in energy intensity will be even greater. A 50% reduction in energy use (with constant population) would put U.S. per capita consumption in line with that of most other industrialized countries.

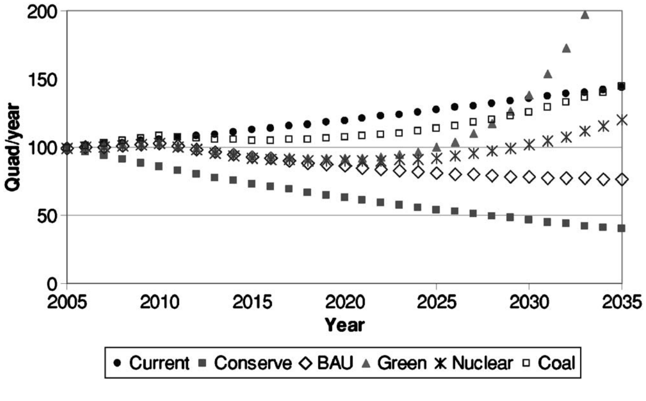

Fig. 12. Summary of energy future scenarios.

VI. EQUITY AND SOCIAL JUSTICE ISSUES

It is widely quoted that the U.S. is responsible for approximately 25% of the world's annual energy consumption, although we have only 5% of the world's population. Furthermore, per capita energy use in the U.S. is much higher than in most other industrialized countries. We can make an argument to justify disproportionate energy use by noticing that the U.S. also accounts for an outsized share of world economic activity, as measured by gross domestic product (GDP), and therefore that the energy intensity of the U.S. economy is not out of line with that of other industrialized countries. At least two general questions come to mind based on these facts. Does the GDP represent a meaningful measure for useful economic activity, or are there other measures we might use to gain an impression of the elusive "standard of living"? And, for whatever measure we do use, what are the implications for world energy use if we profess at least in principle to hope for an improved standard of living for all of humanity?

One measure of human development is given by the human development index. To quote from the United Nations Human Development Report,[39] "The human development index (HDI) is a composite index that measures the average achievements in a country in three basic dimensions of human development: a long and healthy life, as measured by life expectancy at birth; knowledge, as measured by the adult literacy rate and the combined gross enrollment ratio for primary, secondary and tertiary schools; and a decent standard of living, as measured by GDP per capita in purchasing power parity (PPP) U.S. dollars." Any attempt to measure a quantity as complex as human development or human well-being is subject to much criticism and should be treated with caution. We will keep this caution in mind as we look at varying levels of energy use across a range of countries with differing human development indices.

Problem 17. Compare the total and per capita energy and oil use of China, Japan, Germany, Kuwait, Mali, Morocco, Nigeria, Nicaragua, Pakistan, Canada, Venezuela, and the U.S. Compare the energy intensity of the economies of the same countries.

Problem 18. Assume that China continues its current development path, with economic growth of $\approx 8\%$/yr, and that China reaches European levels of GDP and per capita energy use by 2025. What are the implications for world oil demand if (a) 25% of Chinese energy comes from oil, as is currently the case, and (b) if the Chinese wish to rely more heavily on oil in the future (to avoid burning coal, for example), such that 40% of their energy comes from oil, as is roughly the case in the U.S. presently? Make the unlikely additional assumption that all other countries maintain their current energy use.

Problem 19. Assume that European per capita energy usage (roughly half that of the U.S.) is sufficient to allow a reasonable economic development and standard of living. How much energy would be necessary for the entire world to achieve this standard of living? If this human development goal could be reached in 30 years and the energy mix remains constant, what would be the demand for oil in 2035?

Table III. Total and per capita energy use for nine selected countries. The Human Development Index (HDI) is a rough measure of standard of living. In general, higher HDI correlates with higher per capita energy use.

Country	Population (millions)	Total energy use (quadrillion BTU)	Per capita energy use (million BTU/yr)	Total oil consumption (thousand bbl/d)	HDI
Canada	31.6	13.5	427.9	2131	0.949
China	1300	45.4	34.9	5791	0.755
Germany	82.6	14.3	172.7	2664	0.93
Japan	127.7	22.4	175.6	5455	0.943
Kuwait	2.5	0.93	372.3	238	0.844
Mali	12.7	0.015	1.2	4.3	0.333
Morocco	30.6	0.50	16.2	158	0.631
Nicaragua	5.3	0.062	11.7	26	0.69
Nigeria	125.9	0.99	7.9	310	0.453
Pakistan	151.8	1.9	12.4	338	0.527
United States	292.6	99.5	339.9	20,033	0.944
Venezuela	25.8	2.9	113.4	536	0.772

Allow the per capita use of energy in the U.S. to decrease to half its current level, placing us on par with other industrialized countries.

Data. World energy use by fuel: oil 37%, natural gas 24%, coal 27%, nuclear 6%, hydroelectric 6%, out of a total annual energy use of approximately 413 Quads, with U.S. consumption being roughly 23% of this total.[10] These numbers do not include biomass (chiefly wood) as an energy source; doing so would increase the total energy used by about 10%, and lower the other percentages accordingly. The U.S. population is 300 000 000 and expected to continue growing at approximately 1%/yr, the same rate at which world population is expected to grow in the next 30 years from its current level of 6.3 billion.

Data for country-by-country energy use are available from the U.S. Energy Information Administration,[30] and demographic data are available from the International Monetary Fund.[40]

Answer 17. We first look at total energy use and energy use per capita for the nine countries of interest (see Table III). By simply looking at these (selective) data, it would be difficult to generalize about the amount of energy necessary for a country to be considered developed or not. In contrast, a look at the complete set of International Monetary Fund data[40] indicates that all countries with high HDI rankings also use relatively large amounts of energy ($>100 \times 10^6$ BTU/person/yr, ≈ 110 GJ/person/yr), and all countries with a HDI of less than 0.5 use relatively small amounts of energy per capita ($<60\times 10^6$ BTU/person/yr, or 66 GJ/person/yr).

What is more clear is that a country may have a per capita energy use significantly lower than that of the U.S. or Canada, and yet maintain a high standard of living. We will use this information as a rough benchmark for the following calculations.

To determine the energy intensity of the economy, in units of BTU/US$GDP, we can again turn to data from either the International Monetary Fund[40] or the Energy Information Administration.[30] There are two possible methods to arrive at a number, one based on the GDP in units of U.S. dollars, converting the currency of each country to dollars based on world market exchange rates, the other by rescaling of the GDP in US$ based on the purchasing power of the dollar amount in the country in question (purchasing power parity). The two values are shown in Table IV. It is now standard for

Table IV. Economic energy intensity determined by two different measures for nine selected countries. Gross Domestic Product (GDP) can be measured using either market exchange rates (MER) or purchasing power parity (PPP).

Country	GDP/person (US$, MER)	GDP/person (US$, PPP)	Energy intensity (BTU/US$ MER)	Energy intensity (BTU/US$ PPP)
Canada	27,531	31,548	17 863	13 563
China	1098	5087	33 175	6 861
Germany	29,646	27,747	7 545	6 224
Japan	33,705	27,998	4 605	6 272
Kuwait	17,421	18,047	23 023	23 449
Mali	371	994	4 735	1 226
Morocco	1452	4004	12 877	4 046
Nicaragua	745	3262	15 705	3 587
Nigeria	428	1050	18 457	7 524
Pakistan	555	2097	22 342	5 913
United States	37,708	37,353	9 521	9 100
Venezuela	3318	4953	29 326	22 895

Table V. The continued economic growth in China, to the extent that it is tied to the increased use of fossil-fuel energy, has major implications for world demand of finite resources.

Country	Per cap. energy use (million BTU/yr)	Total energy use (Quad/yr)	Per cap. GDP (US$ PPP)	Oil use (25%) (Gbbl/yr)	Oil use (40%) (Gbbl/yr)
China (2005)	35	45	$5 100	2.1	na
China (2025)	163	258	$23 700	11	22
U.S. (2005)	340	99	$37 000	na	7.3

international organizations to use the purchasing power parity numbers when making comparisons involving cost of living and standard of living, and market exchange rates when looking at exports and imports of traded goods.

We make two observations from these data. Just as measures of well-being based on quantities such as GDP must be examined critically, the same holds for the energy intensity numbers as well, because the latter are scaled by the former. Second, we see that there is a fair agreement in values of the energy intensity for many developed countries, when based in terms of purchasing power parity. The U.S. appears (based on this measure) to be somewhat less efficient than Germany, Japan, and even China according to these data. The latter is surprising, and should give some pause for reflection.

Answer 18. To determine the economic implications of continued growth in Chinese energy consumption, we extrapolate population growth by 1% per year and GDP growth by 8%/yr, keeping the energy intensity at the current level. The results of our projection are shown in Table V.

From these assumptions we see that continued GDP growth at current rates would lead to per capita GDP slightly less than that of most developed countries today. (For more accurate purposes of comparison, the growth rates and the GDP values should be considered in real terms, that is, adjusting for inflation.) In 2025, per capita energy use in China in this scenario will be roughly half that currently in the U.S., and similar to current per capita energy use in Europe and Japan. Due to the large population of China, total energy use will be 250% of current U.S. total energy use. To accommodate this change in world energy use, total world energy production would have to increase by 50% in the next 20 years, assuming no increase in annual energy consumption anywhere else in the world.

The implications for world oil demand are particularly startling. If China continues supplying ≈25% of energy needs through petroleum, the country's demand will be 150% of current U.S. oil demand by 2025. For China to supply a percentage of energy needs with oil similar to that of the U.S., its demand would be roughly three times that of current U.S. demand. For the former case, growth in Chinese demand from 2.1 to 11 Gb/yr, that is, by ≈9 Gb/yr, represents 70% of the projected increase in world oil production according to (optimistic) scenarios developed by the Energy Information Administration.[30] In the Energy Information Administration scenario, world oil production in 2025 will be ≈120 MMbd (43 Gb/yr); we saw in Sec. I that a Gaussian fit to the USGS projections gives a peak production rate of somewhat less than 40 Gb/yr. We also mentioned that there is reason to think that those estimates might be too high. If China moves away from coal and toward oil as an energy source, that is, toward the path that other industrialized economies have chosen over the past century, the increased demand by 2025 would be about 20 Gb/yr, far more than the Energy Information Administration projects for world increased production by that time.

There are several points that must be made about these scenarios. We could just as easily have chosen another country, or group of countries, to make clear the ideas we wish to stress. For example, India is rapidly increasing its energy use as well, and has a population of around 1 billion. Because roughly 80% of the world's population lives outside the wealthy developed countries and are for the most part consuming relatively small amounts of energy, we are faced with the dilemma of having to find massive sources of energy in the near future, or else deny developing countries a standard of living anywhere near ours. In an economic paradigm unbounded by natural resource limits, there could always be the hope, however elusive it has thus far been, that the economic development experienced by the U.S. and others is attainable by all countries. It would seem that this model might very well be wrong if the energy sources that drove economic development, industrialization, and modernization will be in short(er) supply in the future. In any case, population pressures will continue to stretch the ability of the world's natural resources to afford a reasonable standard of living for most people.

Answer 19. We can make a quick estimate of the consequences for world energy use. If we look at just the end points, 2005 and 2035, we find that U.S. total energy use decreases from the current 94 to 63 Quads in 2035. For the projected population increase to 390 million in the U.S., yearly energy use would be 162 million BTU per person. At the same per capita energy use and a projected world population of 8.8 billion based on a yearly growth rate of 1%, total yearly world energy demand would be 1360 Quads, 230% of current demand.

For the simple (and unlikely) assumption that the energy mix remains constant, oil would have to supply approximately 500 Quads, or 91 billion barrels per year. These numbers are not possible from any combination of conventional and unconventional sources.

VII. CONCLUSION

One crucial question that remains to be definitively answered is that of the true size of the remaining fossil-fuel resource, and perhaps as importantly, the likely rate of extraction of this resource. We have not addressed the issue of climate change and the potentially disastrous consequences of uncontrolled burning of all remaining fossil fuels,[41] especially if the optimists who count on a large fossil-fuel resource base turn out to be correct. The models (curve-fitting) presented in Sec. I are indeterminate because we may be near an inflection point or a maximum in the various curves.

If we assume a need to make adjustments to our fossil-fuel consumption patterns, there are several important points to be made. First, there are no readily available substitutes for gasoline (or diesel fuel) in the transportation sector, where we use the majority of petroleum. Candidate liquid fuels have either lower energy densities or less favorable net energy characteristics than gasoline and therefore, at the very least, become relatively expensive options. In addition, any large-scale shift in consumption patterns implies a long time scale to make the changes. Because peak oil is near at hand, almost certainly within a decade, there are bound to be significant economic disruptions during the coming transition period.

There is no available silver bullet that would allow an easy transition away from fossil-fuel consumption, with the possible exception of serious reductions in energy use. Renewable energy sources play such a small role in the current overall energy mix that even crash programs would need decade-long efforts to make a large impact on reducing fossil-fuel dependence. Responses to a possible peak in world oil production (followed by a peak in natural gas production) that involve turning toward ever lower net energy fossil-fuel sources will have the further disadvantage that increasing amounts of carbon dioxide will be emitted, thus exacerbating global climate change.

In the developed world, there is room for improvement in energy efficiency. In the developing world, reaching standards of living comparable to those of industrialized countries may be elusive without abundant cheap energy. Some simple estimates indicate that increasing world per capita energy consumption to even half of that in the U.S. is not realistically achievable using fossil fuels, and possibly not with any sources of energy, at least not on a time scale of several decades.

Even before Hafemeister began his series of papers, an initial wake-up call to the world had been issued in the much-maligned work by the Club of Rome,[42] which has since been updated twice. Without going into the details of why this work should still be read, the main points are borne out by the calculations presented in this paper: fossil-fuel resources are finite, exponential growth cannot be sustained in a finite ecosystem, and population increases are placing severe pressures on both the ecosystem and on natural resource supplies.

The issues of energy resources, energy conversion, and alternatives to ever-increasing consumption of fossil fuels are at least as relevant today as they were when Hafemeister originally published his series of papers. Some of the conditions of the discussion appear to have changed in the intervening years; the energy crisis of the late 1970s was clearly the direct result of political events at the time. The current worries about peak oil are the result of more fundamental questions concerning the remaining amounts of what are undeniably finite fossil-fuel resources, along with a world population that is growing and demanding a share of these resources. Regardless of the exact timing of peaks in oil or natural gas production (or even coal production), it is reasonably clear that the students we are teaching now will be going into retirement in a very different world from the one they now experience.

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