

Hydrocarbons and the evolution of human culture

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Most of the progress in human culture has required the exploitation of energy resources. About 100 years ago, the major source of energy shifted from recent solar to fossil hydrocarbons, including liquid and gaseous petroleum. Technology has generally led to a greater use of hydrocarbon fuels for most human activities, making civilization vulnerable to decreases in supply. At this time our knowledge is not sufficient for us to choose between the different estimates of, for example, resources of conventional oil.

The history of human culture can be viewed as the progressive development of new energy sources and their associated conversion technologies. These developments have increased the comfort, longevity and affluence of humans, as well as their numbers. Most of these energy technologies rely on chemical bonds of hydrocarbons. Nature has favoured the storage of solar energy in the hydrocarbon bonds of plants and animals, and human cultural evolution has exploited this hydrocarbon energy profitably.

A key event in the evolution of human society was the development of spear heads and knife blades, devices that allowed humans to exploit a much broader and larger animal-resource base for food and skins. Another was the harnessing of the energy in the hydrocarbon bonds of wood, using fire, which allowed humans to exploit even more food resources, to smelt metals and to bake ceramics. All these developments assisted humans in their exploitation of colder, more northerly ecosystems. The most important of these new energy-based technologies was agriculture, which redirected photosynthetic energy from natural to human food chains.

The principal energy sources of antiquity were all derived directly from the sun: human and animal muscle power, wood, flowing water and wind. About 300 years ago, the industrial revolution began with stationary wind-powered and water-powered technologies, which were essentially replaced by fossil hydrocarbons: coal in the nineteenth century, oil since the twentieth century, and now, increasingly, natural gas. The global use of hydrocarbons for fuel by humans has increased nearly 800-fold since 1750 and about 12-fold in the twentieth century.

Hydrocarbon-based energy is important for the three main areas of human development: economic, social and environmental¹ (Fig. 1). Both the popular and some scientific presses have suggested that we have entered a 'post-industrial' society, where computers and, more generally, human knowledge have replaced raw energy and materials in the generation of wealth. 'Bottom-up analysis', applied by engineers, physicists and some environmentalists, suggests that a substantial decoupling of energy and economic production is now underway². Nevertheless, there continues to be a strong connection between energy and economic activity for most industrialized³ and developing economies⁴.

Top-down macroeconomic analysis indicates that where there is a decline in the ratio of energy to gross domestic product in industrial nations, it is due principally to a shift to higher quality fuels, improvements in fuel efficiency driven by higher fossil fuel prices and structural changes in national economies⁵. Energy prices have an important effect on almost every major aspect of macroeconomic performance, because energy is used directly and indirectly in the production of all goods and services. Both theoretical models and empirical analyses of economic growth suggest that a decrease in the rate of increase in energy availability will have serious impacts⁶. For example, most US recessions after the second World War were preceded by rising oil prices, and there tends to be a negative correlation between oil price changes and both stock prices and returns⁷ in countries that are net importers of oil and gas. Energy prices have also been key determinants of inflation and unemployment.

There is a strong correlation between per capita energy use and social indicators such as the UN's Human Development Index. By contrast, the use of hydrocarbons to meet economic and social needs is a major driver of our most important environmental changes, including global climate change, acid deposition, urban smog and the release of many toxic materials. Increased access to energy also provided the means to deplete or destroy once-rich resource bases, from the megafaunal extinctions associated with each new invasion of spear-equipped humans, to the destruction of natural ecosystems and soils through, for example, over-fishing and intensive agriculture and other types of development. Such problems are exacerbated by the increase in human populations that each new technology has allowed, as well as the overdependence of societies on those once-abundant resources. Energy is a double-edged sword.

How long can we depend on oil?

At present, oil supplies about 40% (natural gas 25%) of the world's non-solar energy, and most future assessments indicate that the demand for oil will increase substantially. What do we know about the future of oil? Predictions of impending oil shortages are as old as the industry itself, and the literature is full of arguments between 'optimists' and 'pessimists' about how much oil there is and what other resources might be available. There are four principal issues



Figure 1 Former oil fields in Southern Louisiana. This area was once a productive salt marsh that contributed greatly to Louisiana's extremely rich fisheries. The numerous straight lines in the picture are the result of past dredging operations to float oil 'rigs' into areas where they extracted oil. The dredging has resulted in enormous land erosion, exacerbated by sea-level increase, which in turn was partly a consequence of greenhouse gas emissions from burning that oil. The oil production is gone, but the environmental degradation remains. Now oil operations have moved offshore, where there are 4,000 energy-intensive oil platforms off Louisiana. There are still oil operations in the coastal region that receive offshore and foreign oil. Louisiana, once the fourth largest oil-producing state (and number one for gas) in the USA, now uses as much oil as it produces and serves mainly as an energy-intensive conduit and processor for foreign oil moving into the US interior (courtesy of Louisiana Department of Wildlife and Fisheries).

that we need to understand to assess the availability of oil, and, by extension, other hydrocarbons, for the future. We need to know: first, the quality of the reserves; second, the quantity of the reserve; third, the likely patterns of exploitation of the resource over time; and fourth, who gets, and who benefits from, the oil. All of these factors ultimately affect the economics of oil production and use.

Quality of petroleum

What we call oil is actually a large family of diverse hydrocarbons whose physical and chemical qualities reflect the different origins and, especially, different degrees of natural processing of these hydrocarbons⁸. In general, humans have exploited the large reservoirs of shorter-chain 'light' oil resources first because larger reservoirs are easier to find and exploit, and lighter oils are more valuable and require less energy to extract and refine. Therefore, over time in mature regions, lower quality has often required the exploitation of increasingly small, deep, offshore and heavy resources (Figs 2 and 3). Progressive depletion also means that oil in older fields that once came to the surface through natural drive mechanisms, such as gas pressure, must now be extracted using energy-intensive secondary and enhanced technologies. Thus, technological progress is in a race with the depletion of higher-quality resources. Another aspect of the quality of an oil resource is that oil reserves are normally defined by their degree of certainty and their ease of extraction, classed as 'proven', 'probable', 'possible' or 'speculative'. In addition, there are unconventional resources such as heavy oil, deep-water oil, oil sands and shale oils that are very energy intensive to exploit.

Quantity of petroleum

Most estimates of the quantity of conventional oil resources remaining are based on 'expert opinion', which is the carefully considered opinion of geologists and others familiar with a particular region (Table 1). The ultimate recoverable resource (URR) is the total quantity of oil that will ever be produced, including the nearly 1 trillion barrels extracted to date. Recent estimates of URR for the world have tended to fall into two camps. Lower estimates come from several high-profile analysts

with long histories in the oil industry. They suggest that the URR is no greater than about 2.3 trillion barrels, and may even be less (for example, ref. 9). A higher estimate of 3 trillion barrels is the middle estimate, and 4 trillion is the highest estimate, from the most recent study by the US Geological Survey (USGS)^{10,11}. About half of the roughly 1.4 trillion barrels that the USGS predicts remain to be discovered are from new discoveries and about half are from reserve growth. The latter describes the process by which technical improvements and correction of earlier conservative estimates increase the projected recovery from existing fields. This relatively new addition to the USGS methodology is based on experience in the US and a few other well-documented regions. The new totals assume, essentially, that petroleum reserves everywhere in the world will be developed with the same level of technology, economic incentives and efficacy as in the US. Time will tell the extent to which these assumptions are realized.

Pattern of use over time

The best-known model of oil production was proposed by Marion King Hubbert, who proposed that the discovery, and production, of petroleum over time would follow a single-peaked, symmetric bell-shaped curve with a peak in production when 50% of the URR had been extracted. This hypothesis seems to have been based principally on Hubbert's intuition, and it was not a bad guess as he famously predicted in 1956 that US oil production would peak in 1970, which in fact it did¹². Hubbert also predicted that the US production of natural gas would peak in about 1980, which it did, although it has since shown signs of recovery. He also predicted that world oil production would peak in about 2000. There was a slight downturn in world production in 2000, but production in the first half of 2003 is running slightly above the rate in 2000.

In the past decade, a number of 'neohubbertarians' have made predictions about the timing of peak global production using several variations of Hubbert's approach. Various forecasts of the year of the global peak have ranged from one predicted for 1989 (made in 1989) to many predicted for the first decade of the twenty-first century to one as late as 2030 (ref. 9). Their predictions begin with an a priori

assumption about the volume of ultimately recoverable oil. Most of these studies assumed world URR volumes of roughly 2 trillion barrels and that oil production would peak when 50% of the ultimate resource had been extracted. In comparison, the USGS low estimate (which they state has a 95% probability of being exceeded) is 2.3 trillion barrels. One analysis fitted the left-hand side of Hubbert-type curves to data on actual production while constraining the total quantity under the curve to 2, 3 and 4 trillion barrels for world URR. The resultant peaks were predicted to occur from 2004 to 2030.

Other forecasts for world oil production do not rely on such curve-fitting techniques to make future projections and/or a priori assumptions about URR. According to the most recent forecast by the US Energy Information Agency (EIA) (2003), world oil supply in 2025 will exceed the 2001 level by 53% (ref. 13). The EIA reviewed five other world oil models and found that all of them predict that production will increase in the next two decades to around 100 million barrels per day, substantially more than the 77 million barrels per day

produced in 2001. Several of these models rely on the new USGS estimates of URR for oil. It should be noted that almost all oil-supply forecasts for which we are able to examine the predictions against reality had a dismal track record, regardless of method. Most recent results of curve-fitting methods showed a consistent tendency to predict a peak within a few years, and then a decline, no matter when the predictions were made¹⁴. It is now a well-established fact that economic and institutional factors, as well as geology, were responsible for the US peak in production in 1970 (ref. 15), forces that are explicitly excluded from the curve-fitting models. Thus, the ability (or the luck) of Hubbert's model (and its variants) to forecast production in the 48 lower states (that is, contiguous) accurately cannot necessarily be extrapolated to other regions. It is too early to tell.

Economic forecasts fare no better in explaining US oil production in the lower 48 states. In the period after the Second World War, oil production often increased as oil prices decreased, and *viva versa*¹⁶, a behaviour that is exactly the opposite of predictions of economic theory. Economic theory also assumes that oil prices will follow an 'optimal' path towards the choke price — the price at which demand for oil falls to zero and the market signals a seamless transition to substitutes. In fact, even if such a path exists, prices may not increase smoothly because empirical evidence indicates that producers respond differently to price increases than they do to price decreases¹⁵. Significant deviation from basic economic theory undermines the *de facto* policy for managing the depletion of conventional oil supplies — a belief that the competitive market will generate a smooth transition from oil. It also suggests the need for a greater degree of government intervention in the transition from oil than is currently envisaged by most policy makers.

Geography

Oil is used by all of the ~220 nations of the world, but significant amounts are produced by only about 42 countries, 38 of which export important amounts. This number is likely to change because of the depletion of the once-vast resources of North and South America, and owing to the increasing domestic use of oil by many of the exporters. The number of exporters outside the Middle East and the former Soviet Union will drop in the coming decades, perhaps sharply, which in turn will greatly reduce the supply diversity to the 180 or so importing nations¹⁷. Such an increase in reliance on West African, former Soviet Union and especially Persian Gulf oil has many strategic, economic and political implications.

Energy and political costs of getting oil

The future of oil supplies is normally analysed in economic terms. But the economic terms are likely to be dependent on other costs. In earlier work we summarized the energy costs of obtaining US oil and other energy resources and found, in general, that the energy returned on energy invested (EROI) tended to decline over time for all energy resources examined. This includes the energy cost of obtaining oil by trading (energy-requiring) goods and services for energy itself¹⁸. For example, the EROI of oil in the US has decreased from a value of at least 100 to 1 for oil discoveries in the 1930s, to about 17 to 1 today for oil and gas extraction (Fig. 4). We are not aware of such estimates for other parts of the world, although we do know that both heavy oil in Venezuela and tar sands in Alberta require a very large part of the energy produced as well as substantial supplies of hydrogen from natural gas to make the oil fluid. The very low economic cost of finding or producing new oil supplies in the Arabian Peninsula implies that it has a very high EROI value, which in turn supports the probability that productivity will be concentrated there in future decades. Alternative liquid fuels such as ethanol from corn have a very low EROI. An EROI of much greater than 1 to 1 is needed to run a society, because energy is also required to make the machines that use the energy, feed, house, train and provide health care for necessary workers and so on.

No one who watches the news can fail to be aware of the impor-



Figure 2 Oil tanker from an oil rig in the North Sea. Copyright Shell International Photographics Services.



Figure 3 Deck of a North Sea oil well. Copyright Shell International Photographics Services.

tance of cultural and political differences between those nations that have the most oil and those that import it. How these factors will play out over the next few decades is extremely important but also impossible to predict. Most of the remaining oil reserves are in Southern Russia, the Middle East and North and West Africa, countries or regions with either Muslim governments or significant Muslim groups. For a long period, frustration and resentment has been building up among Muslim populations, not least because of their perception that the main Western powers have failed to generate even-handed policies to address the conflict in the Middle East over the past half-century. It also is the case that the huge revenues earned by the oil-exporting nations have been very unevenly distributed among their respective populations, adding to internal and external pressure to adopt a more equitable approach to human development. Suffice it to say that there will continue to be high risks of international and national terrorism, overthrow of existing governments and deliberate supply disruption in the years ahead. In addition, exporting nations may wish to keep their oil in the ground to maintain their target price range. Thus, there are considerable political and social uncertainties that could result in less oil being available than existing models predict.

Our need to reduce supply uncertainties

Many once-proud ancient cultures have collapsed, in part, because of their inability to maintain energy resources and societal complexity¹⁹. Our own civilization has become heavily dependent on enormous flows of cheap hydrocarbons, partly to compensate for other depleted resources (for example, fertilizers and long-range fishing boats), so it seems important to assess our main energy alternatives. Some of our most promising new oil fields have turned out to be very disappointing²⁰. If indeed we are approaching the oil scarcity that some predict, it is not reflected in price and few investments are being made at the scale required. An even greater problem may be that an increasing number of decision-makers sense that the market has resolved this issue before and will and should do so again, and also that government programmes are too inefficient to resolve possible

Source	Volume (trillions of barrels)
USGS, 2000 (high) (ref. 11)	3.9
USGS, 2000 (mean) (ref. 11)	3.0
USGS, 2000 (low) (ref. 11)	2.25
Campbell, 1995	1.85
Masters, 1994	2.3
Campbell, 1992	1.7
Bookout, 1989	2.0
Masters, 1987	1.8
Martin, 1984	1.7
Nehring, 1982	2.9
Halbouty, 1981	2.25
Meyerhoff, 1979	2.2
Nehring, 1978	2.0
Nelson, 1977	2.0
Folinsbee, 1976	1.85
Adam and Kirby, 1975	2.0
Linden, 1973	2.9
Moody, 1972	1.9
Moody, 1970	1.85
Shell, 1968	1.85
Weeks, 1959	2.0
MacNaughton, 1953	1.0
Weeks, 1948	0.6
Pratt, 1942	0.6

Source: ref. 21.

impending energy problems. We view this as a recipe for disaster, and it is enhanced by the failure of science to be used as fully as it should be. Thus, in 2003, the state of oil-supply modelling is in some ways no different than it was in Hubbert's time; in other words, a wide range of opinion exists.

What can science do to help resolve this uncertainty? Our principal conclusion is that these critical issues could be and should be the province of open scientific analysis in visible meetings where 'all sides' attend and argue. This analysis should be informed by the peer-review process, statistical analysis, hypothesis-generating and testing, and so on, rather than by the experts one chooses. These issues should be the basis of open competitive government grant programmes, graduate seminars and even undergraduate courses in universities, and our courses in economics should become at least as



Figure 4 Service vessels and infrastructure for off-shore oil facilities in Southern Louisiana.(C. Hall)

much about real biophysical resources, such as hydrocarbon reserves, as about market mechanisms. And we need to think much harder about the alternatives.

The future: other technologies

The world is not about to run out of hydrocarbons, and perhaps it is not going to run out of oil from unconventional sources any time soon. What will be difficult to obtain is cheap petroleum, because what is left is an enormous amount of low-grade hydrocarbons, which are likely to be much more expensive financially, energetically, politically and especially environmentally. As conventional oil becomes less important, society has a great opportunity to make investments in a different source of energy, one freeing us for the first time from our dependence on hydrocarbons.

There are a wide range of options and an equally wide range of opinions on the feasibility and desirability of each. Nuclear power faces formidable obstacles. Experience of the past several decades has shown that electricity from nuclear power plants is an expensive form of power when all public and private costs are considered. Nuclear power generates high-level radioactive wastes that remain hazardous for thousands of years and increases the likelihood of nuclear-weapon proliferation. These are high costs to impose on future generations. Even with improved reactor design, the safety of nuclear plants remains an important concern. Can these technological, economic, environmental and public safety problems be overcome? This remains an unanswered question.

Renewable energies present a mixed bag of opportunities. Some have clear advantages over hydrocarbons in terms of economic viability, reliability, equitable access and environmental benefits. In favourable locations, wind power has a high EROI. The cost of photovoltaic (solar electric) power has come down sharply, making it a viable alternative in areas without access to electricity grids. With proper attention to environmental concerns, biomass-based energy generation is competitive in some cases relative to conventional hydrocarbon-based energy generation. By contrast, liquid-fuel production from grain and solar thermal power has a relatively low EROI. Hydrogen is an energy carrier, not an energy source, but energy and environmental communities have shown enormous interest in its potential. Hydrogen generated from renewable energy sources or electricity-driven hydrolysis is currently expensive for most applications, but it merits further research and development.

Subsidies and externalities, social as well as environmental, affect energy markets. With few exceptions, these subsidies and externalities tilt the playing field towards conventional sources of energy. This presents a clear case for public-policy intervention that would encourage the research, development and adoption of renewable

forms of energy. Policy intervention, in concert with ongoing private investment, will speed up the process of sorting the wheat from the chaff in the portfolio of feasible renewable energy technologies. It is time to think about possibilities other than the next cheapest hydrocarbons, if for no other reason than to protect our atmosphere, and for this task we must use all of our science, both natural science and social science, more intelligently than we have done so far. □

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