The Petroleum Revolution and the First Half of the Age of Oil

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8.1 The First Half of the Age of Oil [1]

This chapter will focus on the importance of fossil fuels (coal, gas, and oil) and especially petroleum (meaning natural gas and oil, or sometimes just oil). First we want to ask why petroleum, and especially oil? Why has petroleum been so important, and why is it so hard to unhook ourselves from it? To do that we need to look more broadly for a moment at the energy situation that has faced, and that faces, humanity. Solar energy, either directly or as captured by plants, was and is the principal energy available to run the world or the human economy. It is enormous in quantity but diffuse in quality. As we have developed in the previous chapter, the history of human culture can be viewed as the progressive development of new ways to exploit that solar energy using various conversion technologies, from spear points to fire to agriculture to, now, the concentrated ancient energy of fossil fuels. Until the past few hundred years, human activity was greatly limited by the diffuse nature of sunlight and its immediate products and because that energy was hard to capture and hard to store. Now fossil fuels are cheap and abundant, and they have increased the comfort, longevity, and affluence of most humans, as well as their population numbers.

But there is a downside, for fossil fuels are made principally of carbon. The use of carbon-based fuels generates a gaseous by-product, carbon dioxide (CO_2) that appears quite undesirable. Now we are constantly bombarded with recommendations of our need to "decarbonize" our economy because of the environmental impacts, such as climate change and ocean acidification that the increases in carbon dioxide appear to be causing. These impacts are likely to become much more important into the future. Consequently there have been considerable efforts to come up with fuels or energy sources not based on carbon. To date that effort has failed completely, for, according to the data compiled by the US Energy Information Agency, the amount of CO_2 produced most years continues to increase (unless there is a recession). With so many apparent options how come we cannot unhook ourselves from carbon? Why is it that most of our energy technologies continue to rely on the chemical bonds of carbon (most usually combined with hydrogen as hydrocarbons)?

The answer lies in basic chemistry: the only effective and large-scale technology that has ever been "invented" for capturing and storing that solar energy is photosynthesis. Humans use the products of photosynthesis for all or most all of our fuels simply because there is no alternative on the scale we need. This is because nature, the source of our fuels, has favored the storage of solar energy in the hydrocarbon bonds of plants and animals. The reasons are that these elements are abundant and "cheap" to an organism, and, most importantly, capable of forming *reduced* or energy-containing chemical compounds. Hydrogen and carbon, which essentially do not exist in elemental form at the Earth's surface, are so important that plants have evolved the technology to split water and atmospheric carbon dioxide to get hydrogen and carbon, which they combine to form energy-rich *hydrocarbons* and, with a little oxygen, *carbohydrates*. There simply are not other elements in the periodic table that are sufficiently abundant and capable of such ready reduction. Nitrogen, for example, is abundant as N_2 but much more expensive energetically to split, and sulfur is less available. In addition carbon has four valence electrons, capable of forming four bonds with other atoms and hence the very complex structures of biology. Bonds with hydrogen greatly increase the capacity to store energy in a molecule. Thus plants and animals are carbon and hydrogen based because nature had no choice. Human cultural evolution has exploited this hydrocarbon energy profitably mostly because they had no choice but to use the products of photosynthesis. Now we are stuck with the carbon dioxide while we try to figure out if there possibly can be an alternative that is energetically feasible.

8.2 The Industrial Revolution

Beginning on a small scale about 1750 but then increasingly rapidly about 1850, there was a rather remarkable change in the hydrocarbons that humans used, from the recently captured solar energy of wood, water and muscle power to the enormously more powerful fossil fuels. This was the beginning of the "industrial revolution," although perhaps a more proper name would

Table 8.1 Energy density of oil and other fossil fuels (may vary somewhat with specific fuels)

Fuel type[a]	MJ/l[a]	MJ/kg[a]	kBTU/Imp Gal	kBTU/US Gal
Regular gasoline/petrol	34.8	~47	150	125
Premium gasoline/petrol		~46		
Autogas (LPG) (60% propane and 40% butane)	25.5–28.7	~51		
Ethanol	23.5	31.1	102	85
Methanol	17.9	19.9	78	65
Gasohol (10% ethanol and 90% gasoline)	33.7	~45	145	121
E85 (85% ethanol and 15% gasoline)	33.1	44	143	119
Diesel	38.6	~48	167	139
Biodiesel	35.1	39.9	152	126
Vegetable oil (using 9.00 kcal/g)	34.3	37.7	148	123
Aviation gasoline	33.5	46.8	144	120
Jet fuel, naphtha	35.5	46.6	153	128
Jet fuel, kerosene	37.6	~47	162	135
Liquefied natural gas	25.3	~55	109	91
Liquid hydrogen	9.3	~130	40	34

Coal 29, *Biomass* 15–28 MJ/GJ
[a]Mj/l = MegaJoules per liter. Neither the gross heat of combustion nor the net heat of combustion gives the theoretical amount of mechanical energy (work) that can be obtained from the reaction. (This is given by the change in Gibbs free energy and is around 45.7 MJ/kg for gasoline.) The actual amount of mechanical work obtained from fuel (the inverse of the specific fuel consumption) depends on the engine. A figure of 17.6 MJ/kg is possible with a gasoline engine and 19.1 MJ/kg for a diesel engine. See brake-specific fuel consumption for more information

be the "hydrocarbon revolution." Humans had begun to understand how to use the much more concentrated energy found in fossil (meaning old) fuels. Why did they do this? The answer is simple. People wanted to do more work because to do so is profitable. They want more of some raw material transformed into something useful that they can eat, trade, or sell. Fossil hydrocarbons have greater energy density than the carbohydrates such as food and wood, and as a consequence they can do much more work—heat things faster and, to a higher temperature, operate machines that are faster and more powerful and so on (Table 8.1). The first fossil hydrocarbon used at any significant scale was coal, first used at a large scale in the nineteenth century, then oil in the twentieth century, and now increasingly natural gas. The global use of hydrocarbons for fuel increased nearly 800-fold since 1750 and about 12-fold in the twentieth century alone, and this has enabled our enormous economic growth (Fig. 8.1).

Economists usually call rapid increases in economic activity development. Hydrocarbon-based energy is important for three main areas of human development: economic, social, and environmental [2]. Most importantly, hydrocarbons have generated an enormous increase in the ability of humans to do all kinds of economic work, greatly enhancing what they might be able to do with their own muscles or with those of work animals by using fossil-fueled machines such as

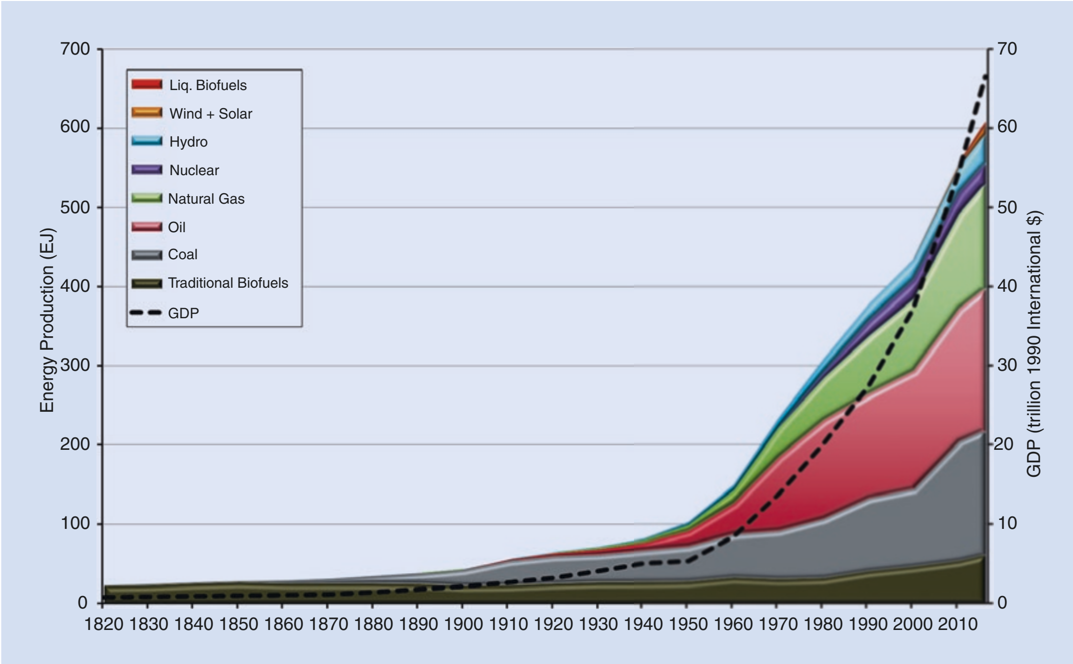

Fig. 8.1 The global use of hydrocarbons for fuel by humans has increased nearly 800-fold since 1750 and about 12-fold in the twentieth century. The most general result has been an enormous increase in the ability of humans to do all kinds of economic work, greatly enhancing what they might be able to do by their own muscles or with those of draft animals (Source: Authors)

trucks and tractors (Table 8.1). Perhaps most importantly this work includes an enormous increase in the production of food.

The industrial revolution started in England with coal in roughly 1750, but by about 1960 the world was using more petroleum than coal, and oil continues to be our most important energy source [3]. Now we live in, overwhelmingly, the age of oil. Some have said that we now live in an information age or a post-industrial age. Both are only partly true. Overwhelmingly we live in a petroleum age. Just look around. All transportation, all food production, all plastics, most of our jobs and leisure, much of our electricity, and all of our electronic devices are dependent upon gaseous and especially liquid petroleum. This has been, and continues to be, the age of oil and of hydrocarbons more generally. Perhaps the industrial revolution should be renamed the "hydrocarbon revolution" because that is what happened—humans moved from using various carbohydrates as their principle means of doing economic work to using hydrocarbons.

One reason that this is the age of oil, and hydrocarbons more generally, is that there continues to be a strong connection between energy use and economic activity for most industrialized [4] and developing economies [5] (Fig. 8.1). Some have argued that through technology and markets, we are becoming more efficient in our use of energy. But the evidence for that is ambiguous at best. As yet unpublished top-down macroeconomic analysis (i.e., simply dividing inflation-corrected GDP by total energy used) undertaken by Ajay Gupta indicates that for most countries of the world, there remains a very strong link between energy use and economic activity, as measured by inflation-corrected GDP and that there is no general trend of countries becoming more or less efficient in turning energy into GDP. One apparent exception is the United States, where there is an apparent decline in the ratio of energy used per unit of gross domestic product. Energy analyst Robert Kaufmann suggests that while there has been some real improvements in fuel efficiency (driven by higher fossil fuel prices), the increases in efficiency are due principally to a shift to higher-quality fuels and especially to structural changes in national economies as richer nations move their heavy industries overseas to reduce pollution or find cheaper labor [6]. There may be another reason as well that the United

States, but few other nations, appears to be becoming more efficient in our use of energy. According to the organization Shadowstatistics, the United States has been engaged in a systematic “cooking of the books” on the official measure of inflation, that is, a deliberate official underestimate of inflation since 1985 to make governments look good. Correcting for any or all of these actions would greatly decrease the perceived improvements of efficiency in the US economy. In addition it is clear from Gupta’s data that the main way that countries develop (i.e., get richer) is through using more energy to do more economic work [7].

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 energy availability will have serious impacts on the economy [8]. 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 their returns in countries that are net importers of oil and gas [9]. 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, although that relation is much more important at low incomes than high—in other words increasing energy use is far more important at improving quality of life for poor than for rich [10]. 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 provided the means to deplete or destroy once-rich resource bases, from megafaunal extinctions associated with each new invasion of spear-equipped humans, to the destruction of natural ecosystems and soils through, for example, overfishing and intensive agriculture and other types of development. Harvard biologist E.O. Wilson has attributed the current mass extinction to what he calls HIPPO effects: Habitat destruction, Invasive species, Pollution, Population (human), and Overgrazing. All these activities are energy-intensive. Such problems are exacerbated by the increase in human populations that each new technology has allowed, as well as the overdependence of societies on previously abundant resources. Energy is a double-edged sword.

8.3 Peak Oil: How Long Can We Depend on Oil?

The critical issue with oil is not when do we run out, but when can we no longer increase or even maintain its production and use. We believe that “peak oil,” the time when humans can no longer count on increasing oil production no matter what their effort, is more or less now and that this will become the most important issue facing humanity. This critical issue can be understood at two levels: first as a simple fact, less, not more, oil over time, and second by a more thorough understanding of the properties and attributes of oil, which we do next. While the exact timing of peak oil for the world remains somewhat debatable, it is clear that it must be soon because each year, we use two to four times more oil than we find. What is even more obvious is that our old rate of increase of 3 or 4% a year has declined since 2004 to from 0 to 1% and that oil availability per capita is declining.

At present, oil supplies about 32% (and natural gas about 20%) of the world’s non-direct solar energy, and most future assessments indicate that the demand for oil will increase substantially if that is geologically, economically, and politically possible. While the use of nonfossil energy resources (e.g., photovoltaic and wind) is increasing rapidly, they still provide only about 2% of global energy use. While the percentage of solar is anticipated to increase, the absolute amount of fossil fuels is predicted to increase for the indefinite future for as long as that is possible. What do we know about the future availability 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 that we need to understand in order to assess the availability of oil and, by extension other hydrocarbons, for the future. We need to know the quality of the reserves, the quantity of the reserve, the likely patterns of exploitation of the resource over time, and who gets and who benefits from the oil. All of these factors ultimately affect the economics of oil production and use.

8.4 Quality of Petroleum

Oil is a fantastic fuel, relatively easy to transport and use for many applications, very energy dense, and extractable with relatively low energy cost and (usually) low environmental impact compared to most other energy sources (Table 8.1). 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 hydrocarbons. Basically oil is phytoplankton kept from oxidation in deep anaerobic marine or freshwater basins, covered by sediments, and then pressure-cooked for 100 million years [11]. 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 require less energy to extract and refine [12]. The depletion of this "easy oil" has required the exploitation of increasingly small, deep, offshore, and heavy resources. Oil must first be found, then the field developed, and then the oil extracted carefully over a cycle that typically takes decades. Oil in the ground is rarely like what we are familiar with in an oil can. It is more like an oil-soaked brick, where the oil must be pushed slowly by pressure to a collecting well. The rate at which oil can flow through these "aquifers" depends principally upon the physical properties of the oil itself and of the geological substrate, but also upon the pressure behind the oil that is provided initially by the gas and water in the well. Progressive depletion also means that oil in older fields that once came to the surface through natural drive mechanisms, such as gas and water pressure, must now be extracted using energy-intensive secondary and enhanced technologies. As the field matures, the pressure necessary to force the oil through the substrate to the collecting wells is supplied increasingly by pumping more gas or water into the structure. EOR or enhanced oil recovery is a series of processes by which detergents, CO_2, and steam have been used—since the 1920s—to increase yields. Too-rapid extraction can cause compaction of the "aquifer" or fragmentation of flows which reduce yields. So our physical capacity to produce oil depends upon our ability to keep finding large oil fields in regions that we can reasonably access, our willingness to invest in exploration and development, and our willingness to not produce too quickly. 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, deepwater oil, oil sands, and shale oils that are very energy-intensive to exploit. Thus while there are large quantities of oil left in the world, the quality of the actual fields is decreasing as we find and deplete the best ones. Now it takes more and more energy to find the next field and, as they tend to be of poorer quality, more and more energy to extract and refine the oil to something we can use.

8.5 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 8.2). The ultimate recoverable resource (URR, often written as EUR) is the total quantity of oil that will ever be produced from a field, nation, or the world, including the 1.3 trillion barrels extracted to date. URR will determine the shape of the future oil production curve. Recent estimates of URR for the world have tended to fall into two camps. There is a great deal of controversy—or rather range of opinion—about how much oil remains (Fig. 8.2). Lower estimates come from several high-profile analysts, many of them retired petroleum geologists, with long histories in the oil industry who suggest that the URR is no greater than about 2.3 trillion barrels (in other words the 1.3 we have used and another 1.0 we will extract in the future), and may be even less [12]. The USGS (United States Geological Survey) "low" estimate is that this number may be about 2.4 trillion barrels, half from new discoveries and half from reserve growth, which is increased estimates of oil available from existing fields. A "middle" estimate is three trillion barrels and the highest credible estimate is four trillion barrels (Table 8.3). These latter three values are from a very comprehensive study by the

Table 8.2 How reliable are official energy statistics? (All values in gigabarrels) (From Lewis L. Smith)

OPEC	Cum prod end 2003	% Depleted	Indicated total	Remaining reserves Gb (as of 2004)				BP estimates interpreted
				PFC	ASPO	Salameh	BP	
Iraq	28	22%	127	99	62	62	115	Total discovered
UAE	19	31%	61	42	49	37	98	Total discovered
Kuwait	32	35%	91	59	60	71	97	Total discovered
Libya	23	39%	59	36	29	26	36	
Saudi	97	42%	231	134	144	182	263	Total discovered
Algeria	13	50%	26	13	14	11	11	
Nigeria	23	50%	46	23	25	20	34	High estimate
Iran	56	51%	110	54	60	64	131	Total discovered
Venezuela	47	58%	81	34	35	31	78	Total discovered
Qatar	6.8	62%	11	4.2	4.1	4.6	15	Total discovered
Indonesia	20	75%	27	6.7	9.4	12	4.4	
Total	**365**		**870**	**506**	**492**	**520**	**882**	

Statistics for the oil industry are not as bad as those for the wine industry, but still, they are pretty bad! This is especially true for reserves; the amounts of oil which engineers and geologists estimate could be extracted in the future from active reservoirs or promising geological formations, given present prices and technology. The three most important compilers of statistics for the oil industry are the BP, *Oil and Gas Journal*, and the US DOE's Energy Information Administration. And that is all they are, compilers. They do not audit, check, or question the information supplied to them by their diverse sources, and they use different definitions of e.g. reserves. One reason is rumored to be that they are afraid of being "cutoff" by any source to which they pose embarrassing questions! Just out of curiosity, I (LLS) checked the table, "Worldwide look at reserves and production," in the December 21 issue of the *Oil and Gas Journal*, pp. 20–21. Of the 200 or so political jurisdictions which merit statistical recognition by the UN, 107 got a line in the table, because they have "proven" oil reserves, gas reserves, or both. There are five good reasons why an estimate of reserves for a nation should change [up or down] every year. Indeed it is almost impossible for them to remain unchanged, if the engineers and geologists have done their work correctly. These five reasons include new findings, revisions in old estimates, and, clearly, production. However, I note that in the referenced table, only 29 countries [27% of the total] report no oil reserves or changed their estimate from last year. The other 78 [73%] reported exactly the same figure for this year as last year. This includes one country which is widely believed to be exaggerating its "official" estimate by more than 100%! Some of the "no changers" include Indonesia, Iraq, Kuwait, Norway, Russia, and Venezuela. Ironically Norway is one of the few countries that publishes good production data by oil field. You may draw your own conclusions! I gather that the situation for natural gas is a little better, but not enough to trust the data for all important producers USGS 2000

Source: Iran's reserves less than half. OPEC's reserves overstated by 80%. From ► mushalik@tpg.com.au and ► http://www.energiekrise.de/e/aspo_news/aspo/newsletter046.pdf

1.1 Trillion	Depleted	Statistical reliability	Production outlook	Technical basis
Actual reserves: 0.9 trillion	Proven >90%	Proven oil in place—high confidence Developed—clear recovery factor Undeveloped—good. recov. est.	Growth thru actual reservoir mgmt. and performance	Improved oil recovery thru existing technology
	Probable >50%	Probable oil in place—confident Developed—prelim. recovery factor Undeveloped—est. fair recovery	Growth thru delineation, testing, and development	Clear opportunity with existing technology
	Potential >5%	Potential oil in place—low confiden. Drilled—v. low recovery factor Undrilled—recovery likely poor	Growth thru pricing, delineation, or IOR/EOR technology	Indicative data and potential opportunity
Contingent resources: 1.1 trillion	Resource: Uneconomic volume and commerciality	Likely presence but undelineated OIP or GIP	Profitability or technology currently inadequate	Available access but lacks good reservoir and fluids data
Prospective and speculative resources: 2.0 trillion	Oil, gas, shales, EHC, and to be discovered resources (speculative outlook)	Technically present but physically inaccessible hydrocarbons	Future resolution thru exploration and relevant technology	General geological, seismic and/or physical indications
		Conceptually possible hydrocarbons, incl. EHCs		

Fig. 8.2 How much oil remains in the world is highly uncertain. For example, "Reserves" are inflated with >300 B bbls of "resources" Source: From ▶ mushalik@tpg.com.au

Table 8.3 Published estimates of world oil ultimate recovery

Source volume (trillions of barrels)	
USGS, 2000 (high)	3.9
USGS, 2000 (mean)	3.0
USGS, 2000 (low)	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

From Hall et al. [1]

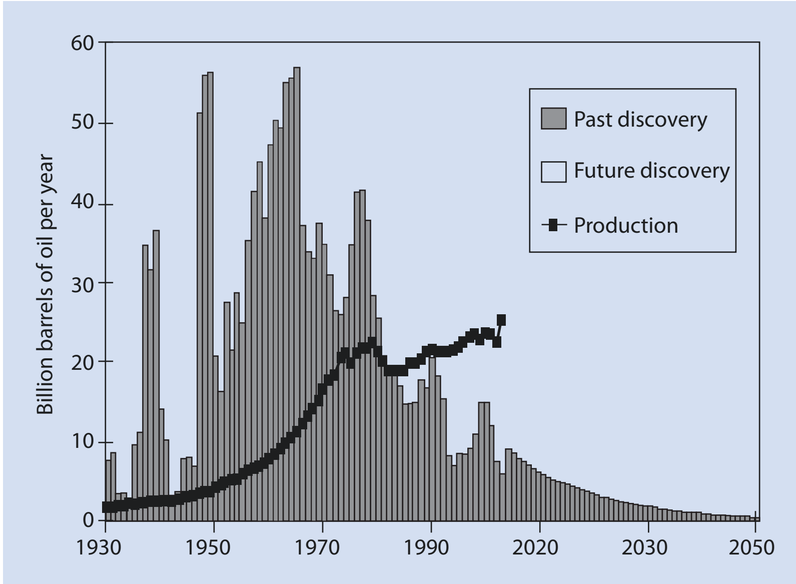

Fig. 8.3 Rates of finding and rate of production for conventional oil globally where field updates have been updated to the year that the initial strike was found (Source: Colin Campbell). Note: There is another way of graphing this data by attributing "revisions and extensions" to the year of revision, not the year of initial strike. This exaggerates the finding rate of more recent years

US Geological Survey in 2000, which if nothing else tend to cover the range of other estimates (USGS [13–15]). Even in that study, the lower values tend to be from their staff of geologists, and the larger ones reflect increasingly the opinion of USGS economists who believe that price signals will allow lower grades of oil to be exploited through technical improvements, and there will be corrections of earlier conservative estimates. This relatively new addition to the USGS methodology is based on experience in the United States 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 United States. Although time will tell the extent to which these assumptions are realized, the last 10 years of data have shown that the majority of countries are experiencing patterns of production that are far more consistent with the low rather than medium or higher estimates of ultimately recoverable reserves (URR) [16, 17]. Increasingly other estimates by, e.g., US and European energy agencies (AIE and IEA), are coming in on the low side. An assessment by oil expert (the best in our opinion) Colin Campbell shows that we are now producing and consuming 2–4 barrels for each barrel we find (Fig. 8.3) One would think that the best way to find and produce more oil would be to drill more, but in fact the finding of oil and gas is almost independent of drilling rate, at least at the levels we have been used to undertaking, because time is needed to determine where the next good place to drill is (Fig. 8.4). The impact of new drilling technology (horizontal drilling and "fracking") is considered in ▶ Chap. 13.

8.6 Pattern of Use Over Time

The best-known model of oil production was derived by Marion King Hubbert, who proposed that the discovery and production of petroleum over time would follow a single-peaked, more or less symmetric, bell-shaped curve (Fig. 8.5). A peak in production would occur when 50% of the URR had been extracted (he later opined that there may be more than one peak). This hypothesis seems to have been based principally on Hubbert's intuition and his tremendous experience examining the patterns of many, many oil fields. It was not a bad guess, as he famously predicted in 1956 that US oil production would peak in 1970, which in fact it did [15]. Hubbert also predicted that the US production of natural gas would peak in about 1975, which it did, although it has since shown signs of recovery and there is a second peak following 2010 based on "unconventional" and "shale" gas. He also predicted that world conventional oil production would peak in about 2000. In fact, conventional oil production continued to increase until 2005, after which it appears to have entered an oscillation or "undulating plateau," as predicted earlier by geologist Colin Campbell.

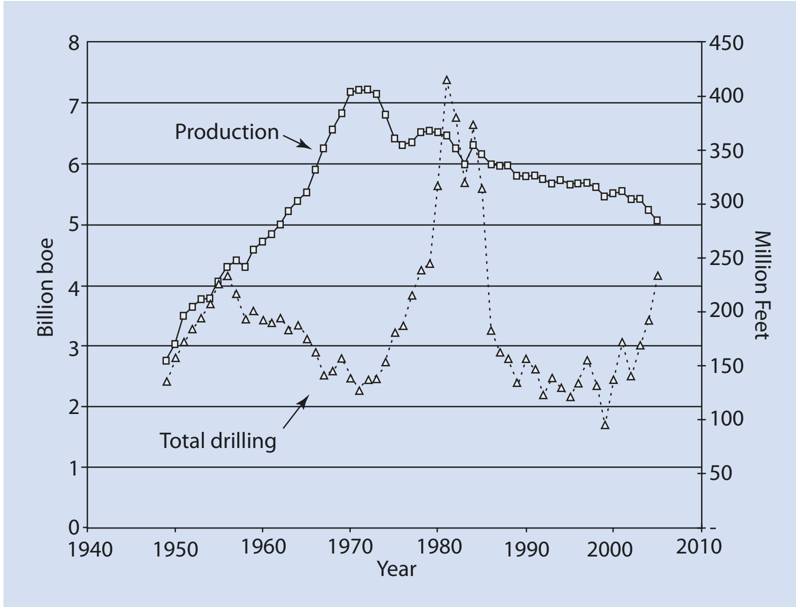

Fig. 8.4 Oil and gas production appears to be independent of drilling effort. There has been essentially no correlation between drilling effort and the rate of finding and (here given) production of oil and gas in the United States except in the first years plotted. Production increased until 1970, then peaked, and then declined steadily despite enormously increased, and subsequent decreased, drilling effort. Drilling rates tend to increase when prices are high and the converse (Source: U.S. EIA; note there has been no data made available since 2007)

8

In the past decade, a number of "neohubbertarians" have made predictions about the timing of peak global production ("peak oil") using several variations of Hubbert's approach [15–24]. These forecasts of the timing of global peak have ranged from one predicted for 1989 (made in 1989) to many predicted for 2005–2015 to one as late as 2030 [18]. Most of these studies assumed world URR volumes of roughly two trillion barrels and that oil production would peak when 50% of the ultimate resource had been extracted. The predictions of a later peak begin with an assumption of a large volume of ultimately recoverable oil. How much oil will we actually recover? The USGS study quoted above gives a low estimate (which they state has a 95% probability of being exceeded) of 2.3 trillion barrels and a "best" estimate of 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 two, three, and four trillion barrels for world URR. The resultant peaks were predicted to occur from 2004 to 2030 [19]. Brandt [20] shows that the Hubbert curve is a good prediction for most post-peak nations, which includes the great majority of all oil-producing nations. Other recent and sophisticated Hubbert-type analyses by Kaufmann and Shiers [21] and Nashawi and colleagues [22] suggest peaks in conventional oil about 2013–2014, consistent with the low URR estimates of, e.g., Campbell and Laherrere, at least as long as there is not much more recoverable oil than seems likely at this time [12]. If that is the case, the peak may be displaced for one or two decades. An important issue that most of these studies do not consider is that most of the oil left in the ground will take an increasing amount of energy to extract.

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 made. This is consistent with the fact that we are using at least twice as much oil as we are finding. Other forecasts for world oil production do not rely on either assumptions about URR or the use of "curve-fitting" or "extrapolating" techniques but simply draw straight lines into the future based on past increases. According to one forecast by the US Energy Information Agency (EIA) (2003), world oil supply in 2025 will exceed the 2001 level by 53% [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 2000 USGS higher estimates of URR for oil. Clouding the empirical assessment is that official estimates are newly including "nonconventional" resources (notably natural gas liquids, but also "heavy" and "ultra-deepwater" petroleum, and

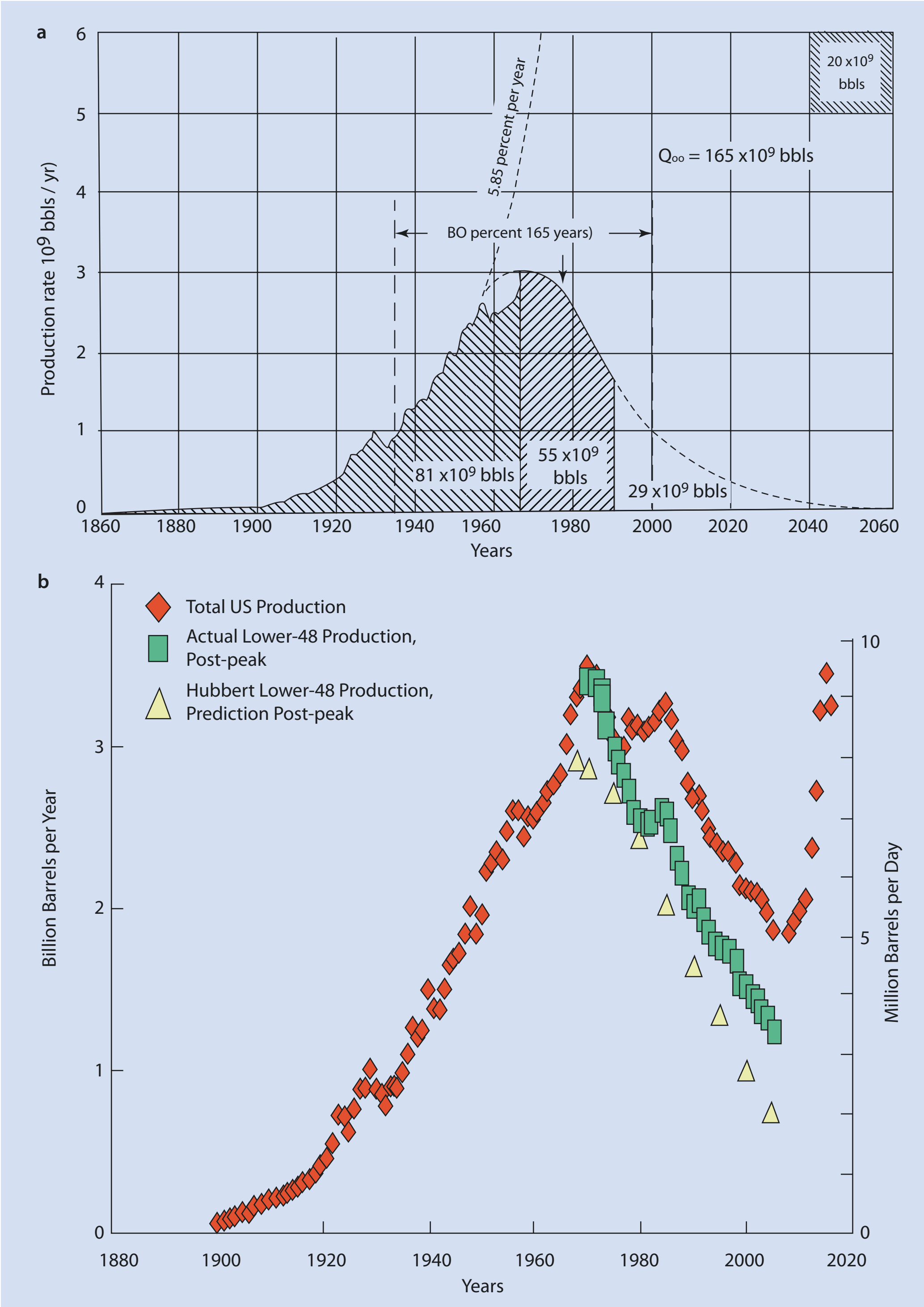

Fig. 8.5 Hubbert curves. **a** Original for United States (Source: Hubbert 1969). **b** Present for United States (Source: 2006 Cambridge Energy Research Associates) and author updates. **c** Original for world (Source: [15]). **d** Present world data (Source: Jean Laherrere ; XH = Extra Heavy (tar sands); LTO = Light, tight (e.g. "fracked" oil. Brown line is what is usually considered "conventional" oil. Thin lines are LaHerrere's predictions). **e** American whaling industry. Depletion was enormous: from 90 to 99% of many whale species were killed (Source: Ugo Bardi)

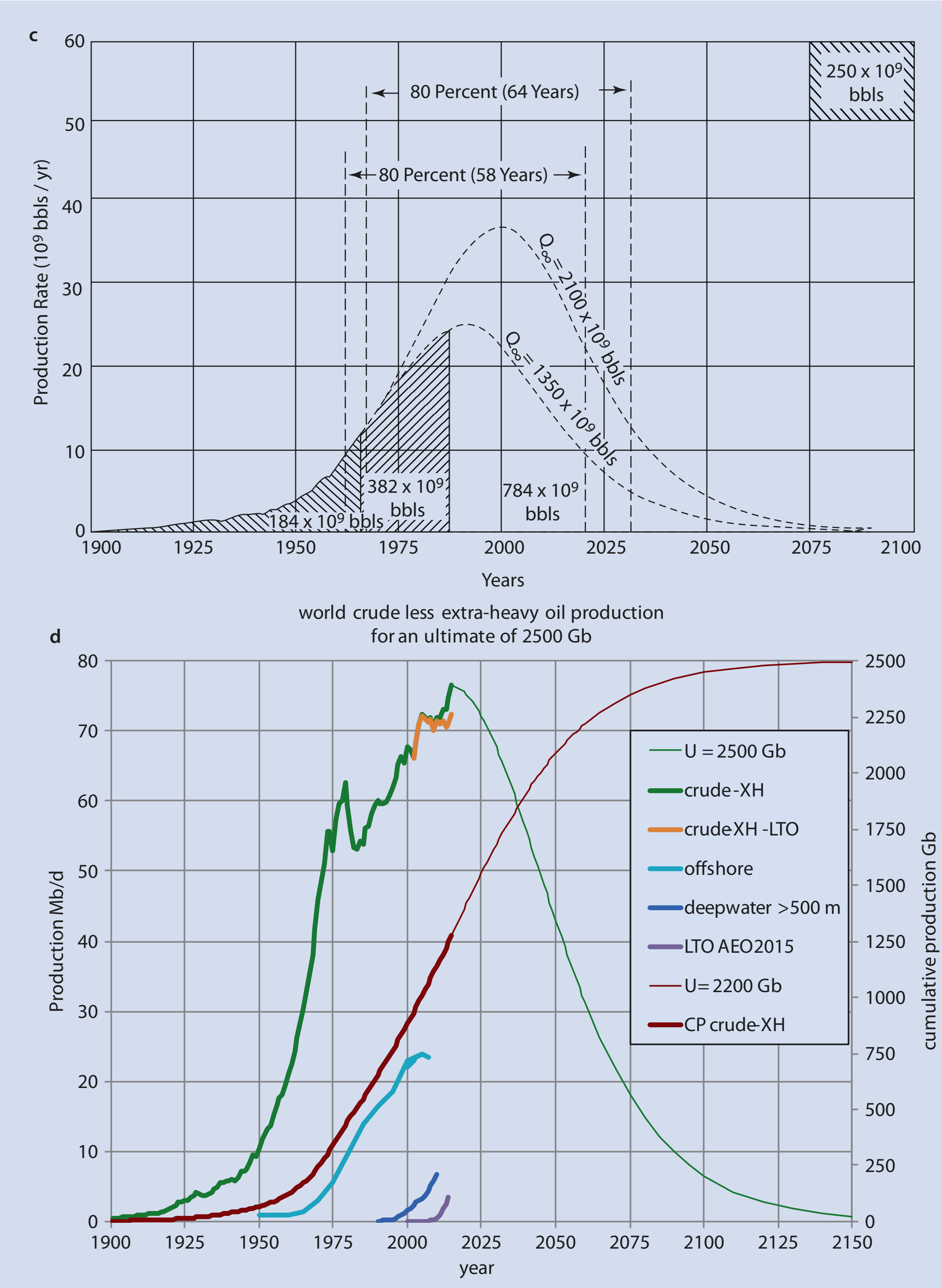

Fig. 8.5 (continued)

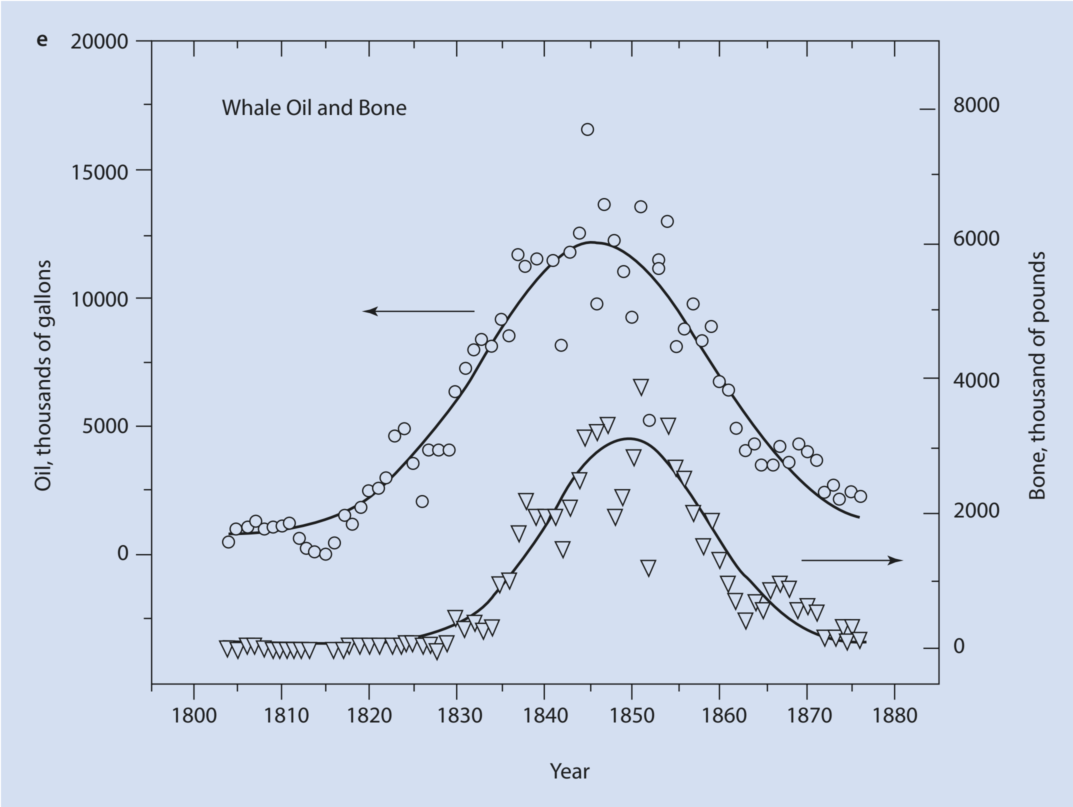

Fig. 8.5 (continued)

biologically derived ethanol) into the empirical estimates of "oil." If these are not included, then the production of conventional oil seems to be essentially flat since 2005 Fig. 8.5d.

It should be noted that the majority of oil-supply and oil price forecasts which we examined (such as that undertaken by Cambridge Energy Research Laboratory and with the possible exception of "post-peak Hubbert" analyses) had a poor track record, regardless of method. 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 [23, 24], 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 accurately should not necessarily be extrapolated to other regions.

On the other hand, one excellent study (in our opinion, but careful, Hall was an author!) by Hallock et al. made predictions for all major oil-producing countries assuming Hubbert curves and using low, medium- and high URR estimates from USGS [13]. They then returned 10 years later and examined the actual behavior of oil production vs. their predictions [16, 17]. They found that the vast majority of oil-producing nations followed a Hubbert curve; most had peaked by 2012 and most followed a path consistent with the USGS low (vs. medium or high) estimates of available oil (Fig. 8.8). Exceptions are several very large oil producers (e.g., Iraq, Iran] whose trajectory is still uncertain due to political events or for whom it is too early to tell. The actual data on global conventional oil production certainly shows at least an undulating plateau from 2005 to 2015 or so at the time of this writing and perhaps even a production peak (Fig. 8.5d). Certainly the old growth rate of 3–4% per year has slowed way down. This is astonishing given the previous continuous growth in production year after year from 1940 through the early 2000s, and this slowdown occurred during times of greatly increasing oil prices. Clearly Hubbert-type peaks have occurred for oil for many nations [17] and for other resources, such as whale oil and perhaps phosphorus (Fig. 8.5e).

So, why is global oil production decreasing or at least no longer increasing? The principle reason is that most oil production comes from very large oil fields (called "elephants"), and we have found very few elephants since the 1960s. Now these large oil fields are aging, and the production in many of these fields is declining by 2–10% a year. Thus while it is true that we are finding additional new oil supplies, these new fields are equal in volume to only about one-fifth of the existing fields, and hence a decline is expected (Fig. 8.6). According to Chris Skrebowski, editor of Petroleum Review, at least one-quarter of the 400 largest oil fields in the world are in decline, and it appears impossible that new oil discoveries, most of which are not large, can possibly make up for the decline in the elephants.

Economic forecasts have not fared well in explaining US oil production. In the period after the Second World War, oil production often increased as oil prices decreased, and vice versa (Fig. 8.4), a behavior that is exactly the opposite of predictions of conventional economic theory. Economic theory also assumes that oil prices will follow an "optimal" path toward the choke price—the price which is sufficiently high to cause the quantity of oil demanded to begin to fall to zero. Thereafter, at least in theory, the market signals a seamless transition to substitutes. In fact, even if such a path exists, prices may not increase smoothly because empirical evidence

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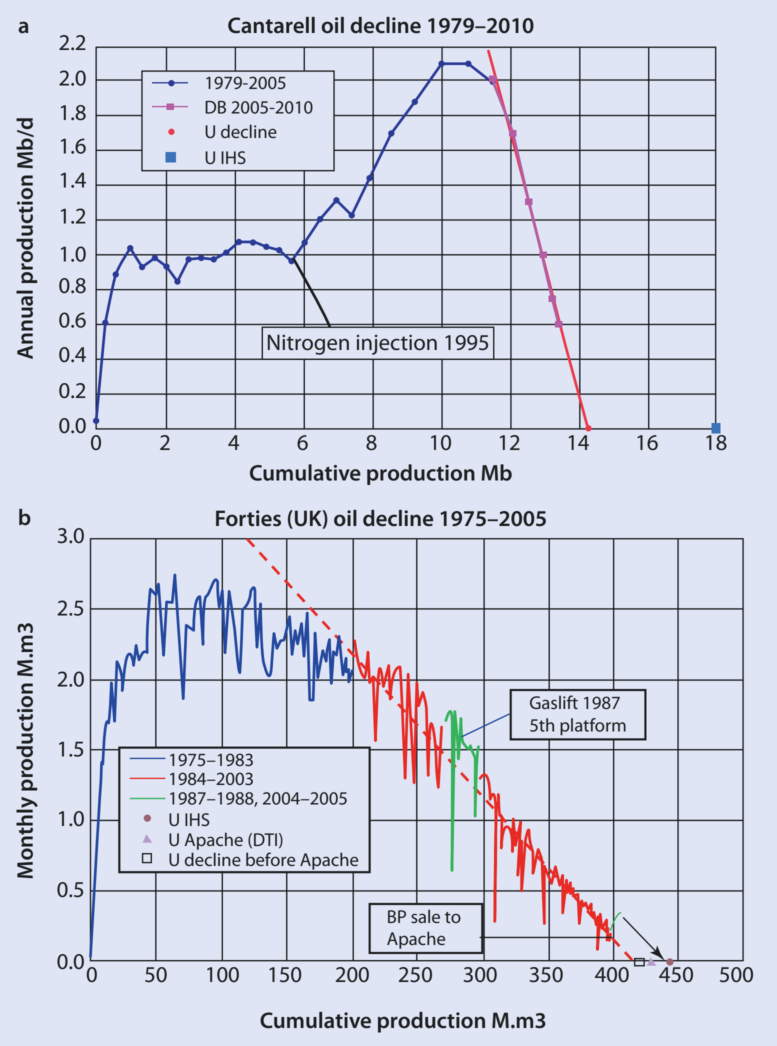
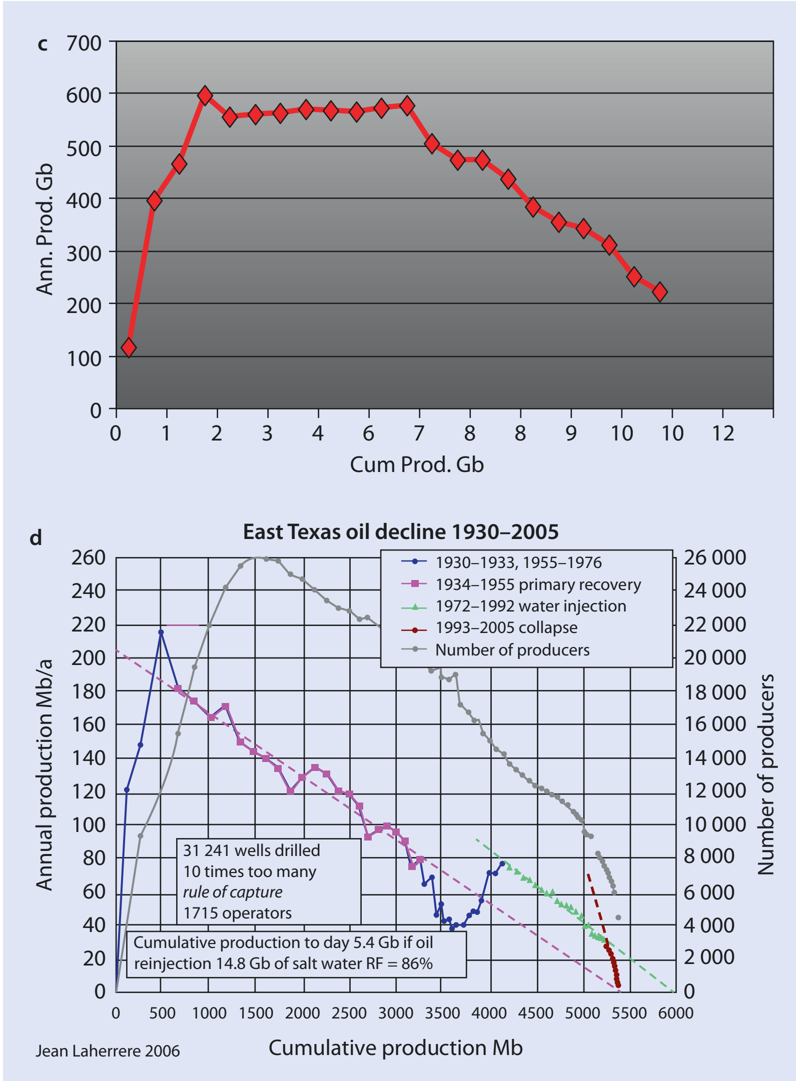


Fig. 8.6 Decline in the production of a number of important "elephants" (Source: Jean Laherrere). **a** Canterell, Mexico, once the world's second largest field. **b** The forties field in the North Sea. **c** Prudhoe field, the largest in the United States. **d** East Texas, the second largest field in the United States

Fig. 8.6 (continued)



indicates that producers respond differently to price increases than they do to price decreases [24]. In the presidential campaign of 2008, one often heard in response to the increased price of oil "drill, drill, drill!." In fact there is little evidence that there is any relation between drilling rate and the production of conventional oil and gas, with the exception of the early 1950s (Fig. 8.4). One way to think about this is that "Mother Nature holds the high cards." In other words oil production will be determined much more by what is geologically possible than by human efforts or economics [12]. 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. We see little evidence of this happening thus far.

Whatever the exact details or the dates of peak oil, it is clear that we are, in the words of Colin Campbell, in transition from the first half of the age of oil to the second half of the age of oil [25]. Each half is and will be equally oil dependent, but the difference will be that between an increasing quantity being used each year to a flat and then decreasing quantity.

8.7 Net Energy from Oil

Our view is that the question is not how much recoverable oil is left in the Earth. We agree that there is a great deal, possibly (but probably not) near the high end of the estimates. But what is missing from the debate is how much of that oil can be recovered with a significant, or perhaps any, net energy gain. These are old arguments about peak oil, but most assessments are made in the absence of net energy costs [26]. If we extrapolate essentially any time series analysis of the net energy returned from oil, all of them show (if present trends continue) a break-even point within decades. Thus we think we will reach the energy break-even point long before we are able to exploit the larger estimates of reserves given by, e.g., the USGS [13] (Fig. 8.7). In other words the total amount of oil in the ground is

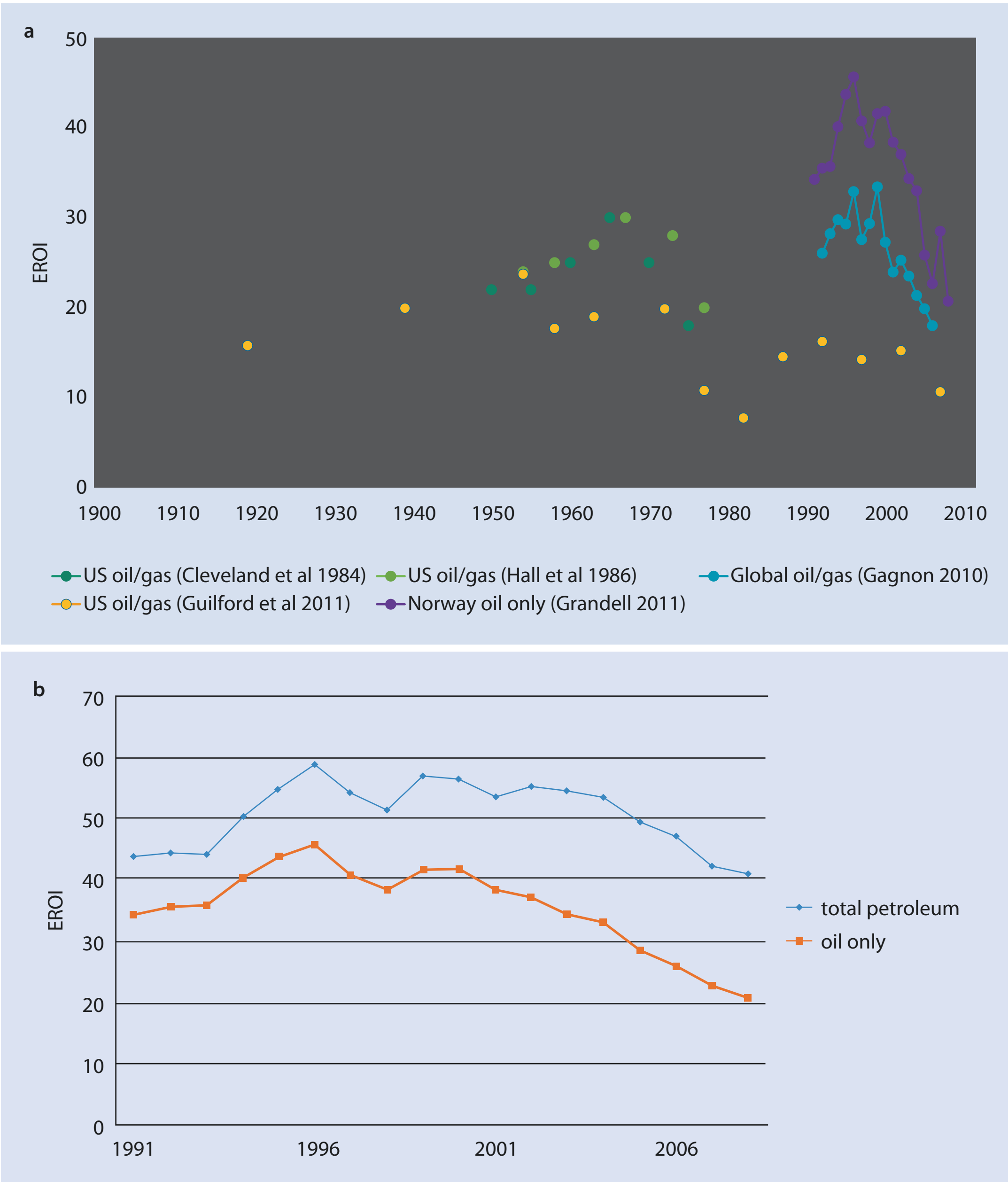


Fig. 8.7 **a** Three estimates for EROI for producing oil in the U.S., along with Estimates for Norway and for all independent oil companies (Source: Hall et al. 2014 and references therein). **b** Example of EROI for oil, and oil plus gas for a country, in this case Norway. One can see the effect of the development, and then gradual depletion, of the important North Sea oil fields. **c** EROI for all fuels for England, including only direct and also direct and indirect energy costs. (From Brand-Correa L.I., Brockway P.E., Copeland C.L., Foxon T.J., Owen A., Taylor P.G., (2017) Developing an Input-Output Based Method to Estimate a National-Level Energy Return on Investment (EROI). Energies 2017, 10(534)

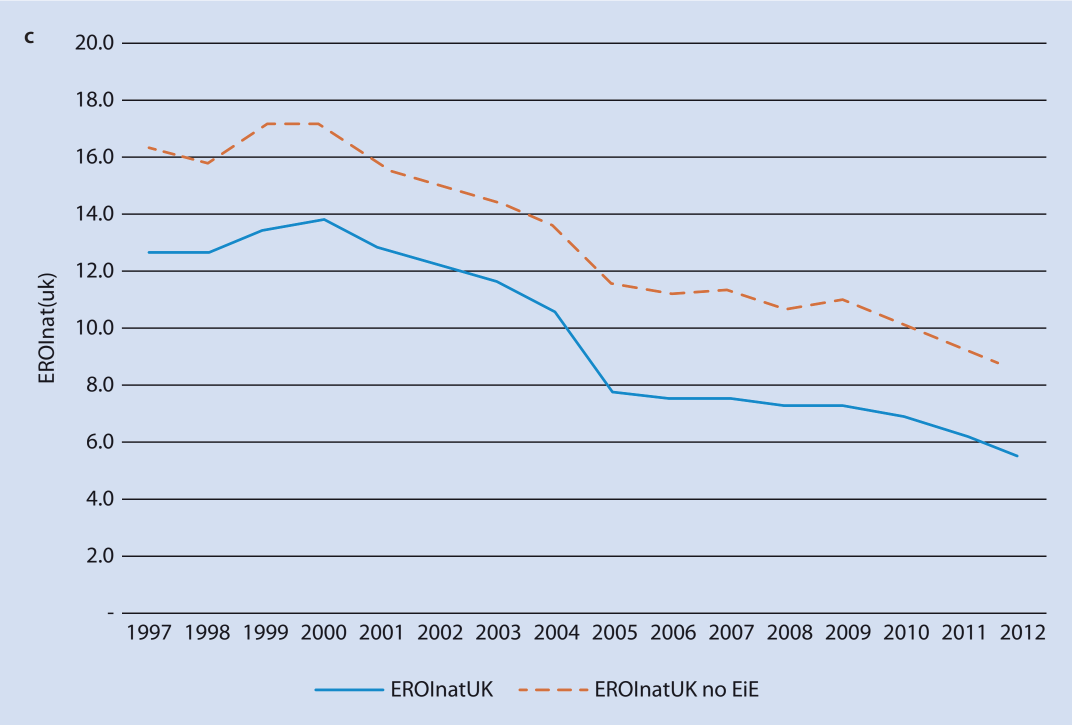


Fig. 8.7 (continued)

not a relevant number. Rather we need to know how much of that can be extracted with a significant net energy profit. This important issue of the energy cost of getting additional quantities of oil, and how that might influence URR, is given in ▶ Chap. 18.

Meanwhile most realistic projections of the availability of all fossil fuels indicate a peak in availability within one or two decades, even including unconventional fuels (e.g. Mohr et al. in 32; Fig. 8.9). Additionally, there may be additional limits to use imposed by efforts to limit climate impacts. However these issues are resolved, it is clear that plans for future economic growth cannot assume that, as in the past, the energy to allow this to happen will be available.

8.8 Geography of Oil

Oil is used by all of the nearly 200 nations of the world, but significant amounts are produced by only about 42 countries, 38 of which export important amounts. This number is declining because of the depletion of the once-vast resources of North and South America, the North Sea, Indonesia, and many other regions 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 160 or so importing nations [27]. Such an increase in reliance on West African, former Soviet Union, and especially Persian Gulf oil has many strategic, economic, and political implications. Much of the world's reserves are found in nations not known to be especially friendly to the United States or the West more generally, in part because of the West's long history of "boots on the ground" expropriation of oil or interference with the governments of producing countries. The EROI for discovering oil and gas in the United States has decreased from a value of more than 200:1 in the 1930s to less than 5:1 in the 2010's, and for production from about 30:1 in the 1970s to less than 10:1 today (Fig. 8.7). The enormously increasing demand for oil from China and their large reserves of money are also likely to have a large impact because the Chinese should have little trouble paying for their oil even as prices raise. On the other hand, the efficiency of using oil may be improving, so that in many OECD countries, there is little or no growth in the use of oil, or even a decline.

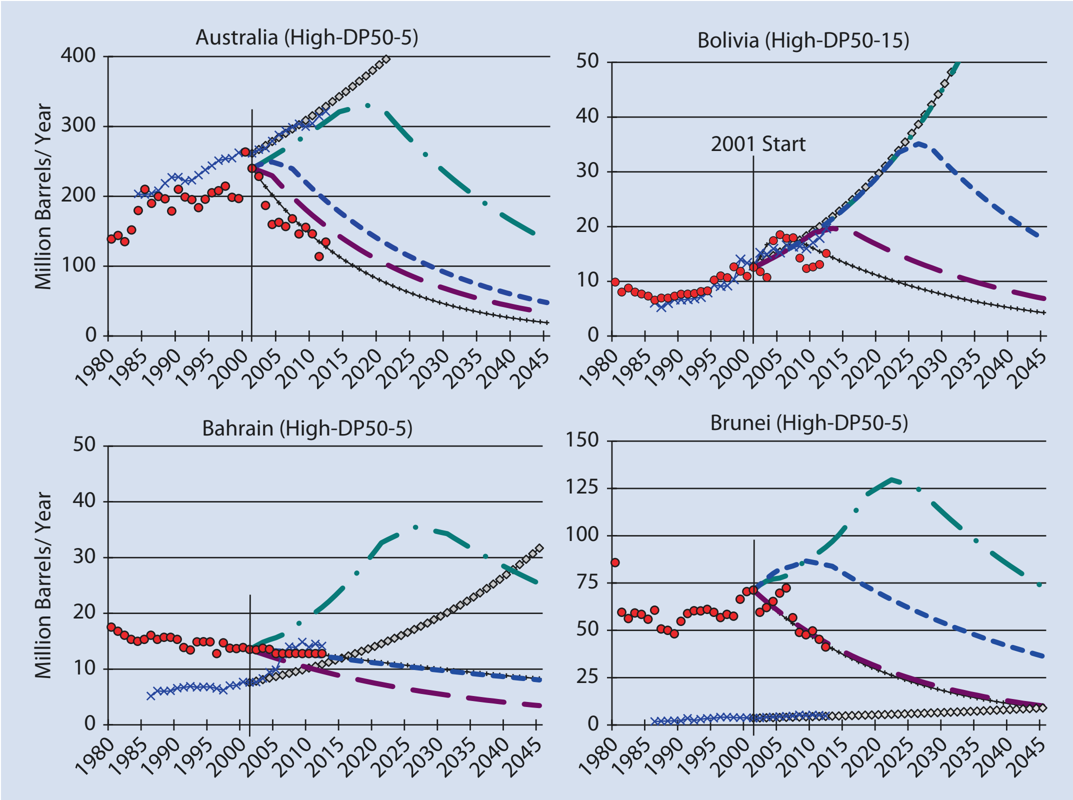


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Fig. 8.8 Typical patterns of oil production for most oil-producing countries showing common patterns of Hubbert Curves for conventional petroleum. *Red dots* represent data. *Blue* and *purple lines* indicate predictions made in 2004 (*vertical line*) for low, medium and high estimates of oil reserves. Crosses and diamonds equal consumption. (Source Hallock et al. 2014; see for all other major producing countries)

8.9 Energy and Political Costs of Getting Oil

The future of oil supplies is normally analyzed in economic terms, but economic costs are likely to be dependent on other costs. In our earlier work [e.g., 26, 27], 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; see ▶ Chap. 18) tended to decline over time for oil and most other energy resources examined. This includes the energy cost of obtaining oil by trading (energy-requiring) goods and services for energy itself [26]. Likewise the EROI for the production of oil and gas globally has declined from about 36:1 in the 1990s to about 19:1 in 2006 [27]. In other words, with all of our super technology we can continue to get oil and gas, but the energy cost per barrel continues to increase as we deplete the best resources. This is also true for such estimates for other parts of the world, and we do know that both heavy oil in Venezuela and oil 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 [28]. 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 production will be concentrated there in future decades. Alternative liquid fuels, such as ethanol from corn, have a very low EROI, perhaps not even a positive gain over the fossil fuels invested to plant and distill the alcohol [29]. An EROI of much greater than 1:1 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 (▶ Chap. 19).

No one who watches the news can fail to be aware of the importance 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 populations. For a long period, frustration and resentment have been building up among many Muslim populations, not least because of their perception that the main Western powers have failed to generate even-handed policies to address the conflicts in the Middle East over the past half century. Iranians still have vivid memories of the role the Central Intelligence Agency played in the overthrow of their democratically elected prime minister, Dr. Mohammed Mossadeq, on behalf of the Anglo-Iranian Oil Company (now BP). Another factor is 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. The "Arab spring" of 2011, where new pressures for governmental reform have greatly increased the instability of many Middle Eastern oil-producing nations—and oil prices for at least a few years. Much of the unrest stems in part from the failure, and some would say impossibility, of these economies to produce sufficient jobs and even food for their growing populations. 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 [Ahmed in 35]. 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.

8.10 Deep Water and Extreme Environments

Although considerable uncertainty remains about how much oil we will extract, eventually one thing is clear: oil is getting harder and harder to find [25–33]. This can be seen by the increasing dollar, energy, and environmental cost of getting oil and by the fact that we are undertaking major exploration and development in areas (such as very deep ocean) that were thought too difficult and expensive just a decade ago, so that half of new US drilling effort now takes place far offshore. There have been amazing developments in technology that have allowed this new exploration: drilling ships unanchored to the bottom kept in place by GPS systems and huge thrusters, drill strings that go down through 2000 meters of ocean and then 5000 meters or more of rock, and so on. The Deepwater Horizon oil spill of 2010 in the Gulf of Mexico has brought all these operations to the attention of the public, and one of the first questions asked was: why are we working in such a difficult and potentially dangerous environment? The answer is that while the oil fields that have been discovered at these depths appear to be the only large fields left that have not yet been exploited—in other words we went after the easy stuff first and left the most difficult until later. So if we are to continue to have oil, we need to undertake these expensive and risky operations. The most interesting analysis of this issue is by Tainter and Patzek [34], where the authors ask whether we have expanded the complexity of our American "empire" to the point that the energy cost of getting energy itself to the center of the "empire" exceeds the gain from that energy. They point out that this may be analogous to other ancient empires (such as Rome) which expanded until they reached the limits of managing the complexity necessary for maintaining the society [35]. A similar analysis might be made of our large efforts in militarization in support of maintaining oil flows.

A final important issue relating to the development of new oil or its possible substitutes has been put forth by Robert Hirsch and his colleagues in several extremely insightful papers [36, 37]. Their basic point is that a critical element in finding a substitute for petroleum (if indeed a substitute exists) is time—that is, even if a workable substitute can be found (and they examine, e.g., shale oil, biomass fuels and even greatly increasing the gas mileage of our vehicles) and assuming that government (or private) programs can be developed and money is no object that it would take decades simply to scale up the approach. In other words if we could maintain liquid-fuel use at the level of the peak of oil (perhaps about what we have in 2005–2010), it would take decades to construct the needed infrastructure. The importance of trucks to our present way of life and the implications of not having enough petroleum to run them have been wonderfully assessed by Alice Friedemann [38]. It is a very sobering perspective.

8.11 How About Natural Gas?

Petroleum usually means liquid and gaseous hydrocarbons and includes oil, natural gas liquids, and natural gas. Thus a chapter on oil is incomplete without some consideration of natural gas. Natural gas is often found associated with oil, although it has other possible sources, including coal beds and organic-rich shales. Oil is a natural hydrocarbon where the original plant material, often composed of hundreds to thousands of carbons linked together, has been cracked or broken by geological energies to a length of (ideally) eight carbons (octane). If the cracking continues to the extreme, the carbon bonds are broken completely to a length of one carbon, usually surrounded by four hydrogen molecules, a gas called methane. This makes gas an ideal fuel because oxidizing hydrogen releases more energy and releases less carbon dioxide than oxidizing carbon. Methane is much more easily obtained, stored, and moved than is hydrogen, partly because the much smaller hydrogen molecule leaks more easily. When natural gas is held in a tank, some heavier fractions fall out as natural gas liquids, and these materials can be used, essentially, either directly or as inputs to refineries. Natural gas was once considered an undesirable and dangerous by-product of oil production, and it was flared into the atmosphere. With time its commercial value was recognized and a complex pipeline system evolved. Now natural gas is more or less tied with coal as the second most important fuel in the United States and the world. An important question is: if oil falters can natural gas take over its role? It can even be used to propel vehicles with minimal changes to the engine, and it has essentially displaced the role of oil in electricity production. It is not as energy dense or transportable as oil, but it comes close, and because it is clean it has many special uses such as for baking and as a feedstock for plastics and nitrogen fertilizer.

Beginning in 2010 there was a great deal of excitement and debate about whether "unconventional" natural gas from, e.g., the Marcellus shale, can provide an energy renaissance for the United States. While it has been known that considerable gas exists in association with certain shales, it was too difficult to get out because the shale formations were too thin and a conventional vertical well simply passed through the formation without intercepting much gas. New technologies, including horizontal drilling and fracturing or "fracking" the rocks with very high-pressure water, have allowed considerable amounts of gas to be produced. But since the environmental impacts are barely known and possibly large, and tens of thousands of wells are needed to get a significant amount of gas, there is large controversy about the degree these wells should be drilled. Something less well known is that most of the gas in those areas we know best (e.g., the Barnett shale in Texas) comes from a relatively few "sweet spots" and that the total regional production may go through most of a full Hubbert cycle in only 15 years. Meanwhile conventional gas production has peaked and dropped off to less than half the peak, so that so far the unconventional gas of all kinds is simply compensating for the drop-off of conventional gas (Fig. 8.10). Thus natural gas is likely to be very important as oil production and availability decline, and it will extend the petroleum age by a few decades. But then that too will be gone, and the United States will be left with little domestic production of domestic oil or gas. The younger people reading this book will have to deal with the decline and even termination of the petroleum age (Fig. 8.9).

8.12 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 scarce is cheap petroleum, the kind that allowed industrial and economic growth. 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 available, society has a great opportunity to make investments in different sources of energy, perhaps 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 can be a reliable and mostly safe source of electricity, although expensive form of power, when all public and private costs are

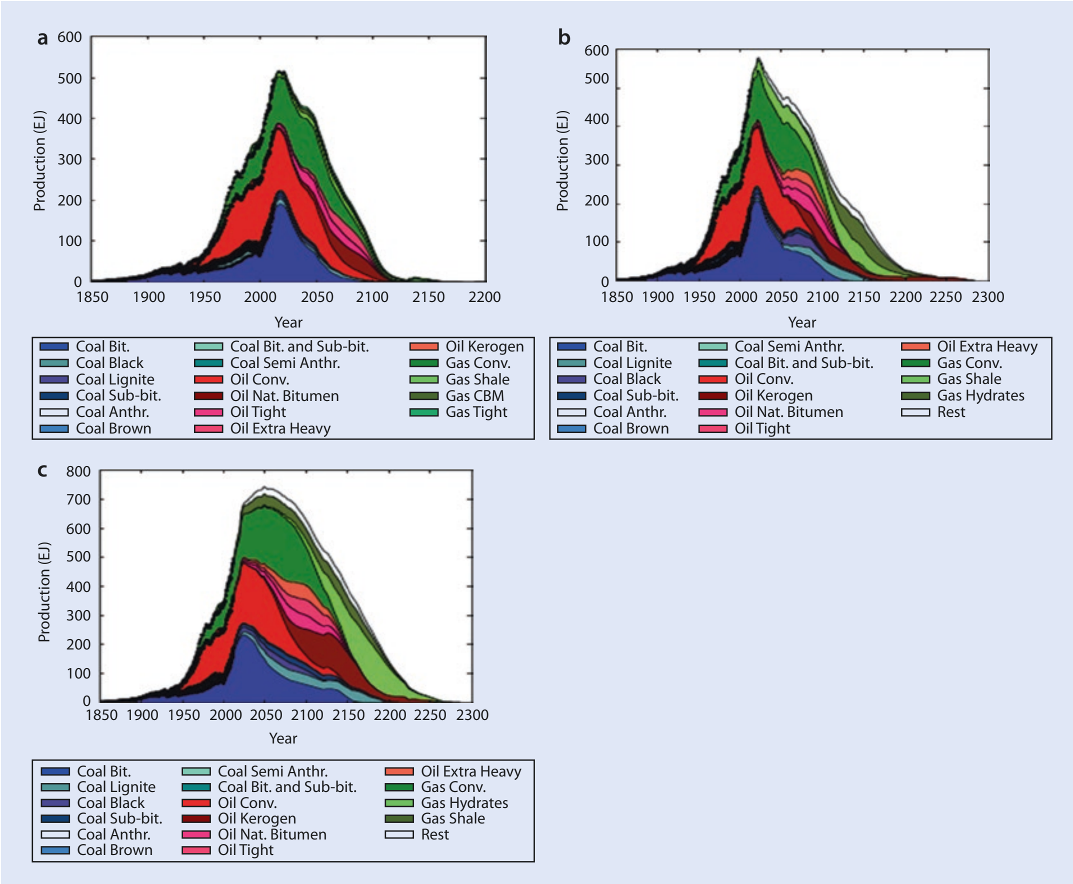

Fig. 8.9 Data on, and prediction of future usage of all fossil fuels using low (**a**), "best" (**b**) and high (**c**) estimates of supplies (From Mohr et al. 2015). Similar patterns have been found by other investigators

considered. The earthquake-tsunami-induced accident at Fukishima may make continued expansion unlikely in many nations. Other unresolved issues include that nuclear power generates high-level radioactive wastes that remain hazardous for thousands of years, possible nuclear weapons proliferation, and whether there is enough uranium to allow a significant contribution to global energy supplies. These are high costs to impose on future generations. Even with improved reactor design, the safety of nuclear plants remains an important concern. Can commercial nuclear power be divorced fully from nuclear weapons proliferation? Can these technological, economic, environmental, and public safety problems be overcome? Can new reactors using thorium fuel be created that decrease the problem of dangerous by-products generated from uranium while expanding the fuel supplies? These questions remain unanswered while we increase our use of fossil fuels essentially every year.

Renewable energies present a mixed bag of opportunities. Some argue that they have clear advantages over hydrocarbons in terms of economic viability, reliability, equitable access, and especially environmental benefits. But nearly all suffer from very low energy return on investments compared to conventional fossil fuels. In favorable locations, wind power has a high EROI (18:1 or more). The cost of photovoltaic (solar electric) power has come down sharply, making it a viable alternative in areas without access to electricity grids, but the EROI remains relatively low, perhaps only 4:1 or less, when considered on a systems level although some argue that because the input tends to be fossil fuel and the output electricity the realized EROI is considerably higher [39]. Both of these solar energies require very expensive backups or transmission systems to compensate for intermittent production, as they are available only 20–30% of the time. With proper attention to

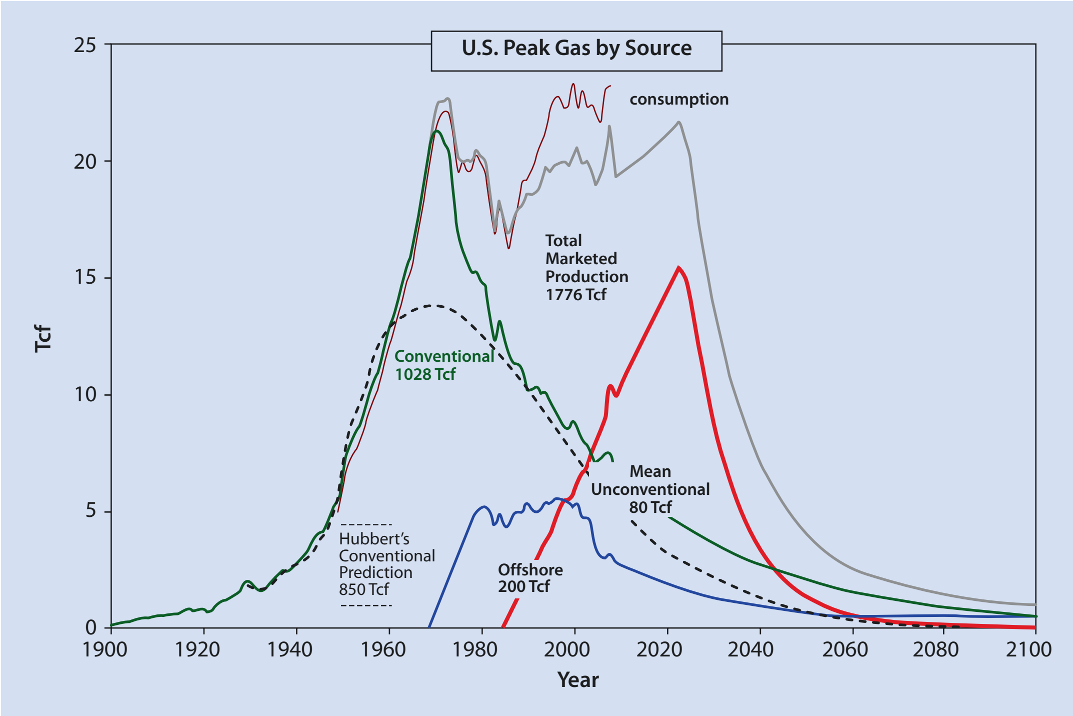

Fig. 8.10 Patterns of past and projected production of conventional, deepwater, and unconventional (e.g., shale gas) US natural gas (Source: Bryan Sell, Sustainability, in 2011)

environmental concerns, biomass-based energy generation is competitive in some cases relative to conventional hydrocarbon-based energy generation. At present liquid-fuel production from grain has a relatively low EROI [34, 35]. Hydrogen, advocated by many, is an energy carrier, not an energy source, and thus requires some kind of fuel to be used to split water or run some other process to generate the hydrogen. Additionally there are many problems to overcome because the small molecules leak easily and are hard to store. Hydrogen generated from renewable energy sources or electricity-driven hydrolysis is currently expensive for most applications, but it merits further research and development.

A disquieting aspect of all these alternatives, however, is that as energy delivery systems (i.e., including backups, transmission, etc.), they all have a much lower EROI than the fossil fuels we would like them to replace, and this is a major reason for their relatively low economic feasibility in most applications [32]. This may be changing rapidly now, we shall see. But going to half renewables would be an extremely tough nut to crack. Subsidies and externalities, social as well as environmental, add difficulties to this evaluation but are poorly understood or summarized. This presents a clear case for public policy intervention that would encourage a better understanding of the strengths and weaknesses of renewable (and traditional) forms of energy. Policy intervention, in concert with ongoing private investment and also markets, may be necessary to speed up the process of sorting the wheat from the chaff in the portfolio of renewable energy technologies, necessary if for no other reason than to protect our atmosphere.

8.13 The Social Importance of These Supply Uncertainties

Many once-proud ancient cultures have collapsed, in part, because of their inability to maintain energy resources and societal complexity [35]. Our own civilization has become heavily dependent on enormous flows of cheap hydrocarbons, partly to compensate for other depleted resources (e.g., through fertilizers and long-range fishing boats), so it seems important to assess our main energy alternatives. Oil is quantitatively and qualitatively most important. Investments in oil have continued to increase, but supply remains flat and is likely to decrease. Some of the most promising new oil fields have turned out to be very disappointing [32, 33]. Global findings in 2016 were only about 10% of global use. If indeed we are approaching the oil scarcity that some predict, it is barely reflected in oil prices, and few investments in alternatives are being made at anything like the scale required to replace fossil hydrocarbons—if indeed that is possible. Unfortunately the majority of decision-makers hold on to the fantasy that the market has resolved this issue before and will do so again. Further, an increasing number of US citizens believe that government programs are too ineffective to resolve any problem, including energy problems. We view this is a recipe for disaster. It is enhanced by the failure of science to be used as fully, effectively, or objectively as it should be. Failures in proper government funding for good energy analysis have led to the dominance of "science" in the media and decision-making whose role is basically to support the predetermined position of those who support it. In 2017 the state of official oil-supply modeling is in some ways no different than it was in Hubbert's time: a wide range of opinion exists and there is little or no objective and reliable overview.

This issue is critical at this point in time because if civilization is to survive the next 50 years, enormous new investments are necessary in whatever we will need to replace existing flows of conventional oil and gas and even coal. Energy costs now are only for the costs to extract fuels from existing reserves, not to come up with replacements once those fuels are gone. As energy prices increase, citizens are probably not going to be too excited to pay even more for a program to develop the research and infrastructure to generate replacement fuels, even if we knew what they should be. According to one of our best energy analysts, Vaclav Smil, at this time there seems to be few really good options except to decrease our appetites for energy [40].

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 and where financial resources are provided to objective analysts to reduce uncertainty and understand different assumptions. This analysis should be informed by professionalism, the peer review process, statistical analysis, hypothesis generation and testing, and so on, rather than by simply the opinions of the experts one chooses or the quips on the blogosphere. These issues should be the basis of open competitive government grant programs, graduate seminars, and even undergraduate courses in universities, and our courses in economics should become at least as much about real biophysical resources, such as hydrocarbon reserves, as about market mechanisms. Also, we need to think much harder about the alternatives, including their energy cost of implementation and also the need to develop a lower energy-using society. None of this appears to be part of the plans of any existing government or governmental agency in the United States or most other industrial countries.

? Questions

1. What is meant by the phrase "the first half of the age of oil"?
2. What are energy-dense materials?
3. We have been told that we live in an "information age." Argue for or against that statement.
4. Is peak oil a fact or a concept? Defend your view.
5. What does EUR mean? How is it related to peak oil?
6. What were Hubbert's basic ideas?
7. If there are huge amounts of oil left in the Earth, does this imply adequate supplies for the foreseeable future? Why or why not?
8. How is natural gas related to oil?
9. What does "cheap oil" mean relative to the remaining oil we might be able to extract from the Earth?
10. With many alternatives, why do you think that we have continued to rely so much on oil and other hydrocarbons?

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