19

Peak Oil, EROI, Investments, and Our Financial Future

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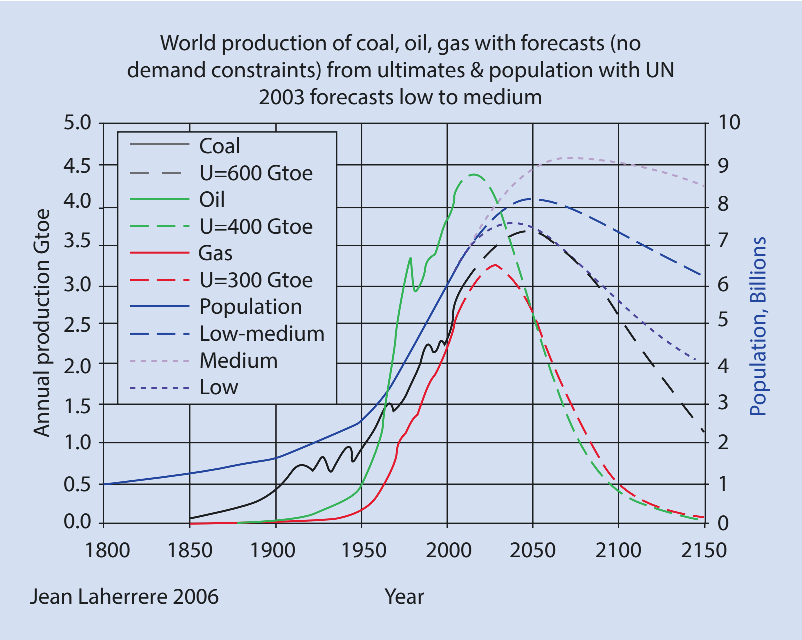
19.1 Introduction

The enormous expansion of the human population and the economies of the United States and many other nations in the past 100 years have been facilitated by a commensurate expansion in the use of fossil fuels (Fig. 8.1) [1]. To many energy analysts, that expansion of cheap fuel energy has been far more important than business acumen, economic policy, or ideology, although they too may be important [1–15]. While we are used to thinking about the economy in monetary terms, those of us trained in the natural sciences consider it equally valid to think about the economy and economics from the perspective of the energy required to make it run. When one spends a dollar, we do not think just about the dollar bill leaving our wallet and passing to someone else's. Rather, we think that to enable that transaction, that is, to generate the good or service being purchased, an average of about 5000 kJ of energy (roughly half the amount of oil that would fill a standard coffee cup) must be extracted and turned into roughly a half kilogram of carbon dioxide. Take the money out of the economy and it could continue to function through barter, albeit in an extremely awkward, limited, and inefficient way. Take the energy out and the economy would immediately contract or stop. Cuba found this out in 1991 when the Soviet Union, facing its own oil production and political problems, cut off Cuba's subsidized oil supply. Both Cuba's energy use and its GDP declined immediately by about one-third, groceries disappeared from market shelves within a week, and soon the average Cuban lost 20 pounds [16]. Cuba subsequently learned to live, in some ways well, on about half the oil as previously, but the impacts were enormous. While the United States has become more efficient in using energy in recent decades, most of this is due to using higher-quality fuels, exporting heavy industry, and switching what we call economic activity (e.g., [17]), and many other countries, including efficiency leader Japan, are becoming substantially less efficient [18–20].

19.2 The Age of Petroleum

The economy of the United States and the world is still based principally on "conventional" petroleum, meaning oil, gas, and natural gas liquids (Fig. 19.1). *Conventional* means those fuels derived from geologic deposits, usually found and exploited using drill bit technology. Conventional oil and gas flows to the surface because of its own pressure or with pumping or additional pressure supplied by injecting natural gas, water, or occasionally other substances into the reservoir. *Unconventional* petroleum includes shale oil, oil

Fig. 19.1 Pattern of past fossil energy use and human population for the world, including projections (Gtoe = Giga tons oil equivalent. Source: Jean Laherrere)



sands, and other bitumens usually mined as solids and converted to liquids and also natural gas from coal beds and/or "tight" deposits where the gas is found in low concentrations in rock. For the economies of both the United States and the world, from half to two-thirds of our energy comes from conventional petroleum, about 30–40% from liquid petroleum, and another 20–25% from gaseous petroleum (◘ Fig. 19.1). Coal, hydroelectric, and nuclear provide most of the rest of the energy that we use. Hydroelectric power and wood together are renewable energies generated from current solar input and provide about 5% of the energy that the United States and world uses, "New renewables" including windmills and photovoltaics generate about 2%. In recent years the annual increase in oil and gas use has been greater than the power coming from the new renewables or indeed their total production so that they are mostly not displacing fossil fuels but just adding to the mix. All of these proportions have not changed very much since the 1970s in the United States or the world. We believe it is most accurate to consider the times that we live in as *the age of petroleum*, for petroleum is the foundation of our economies and our lives. Just look around.

Petroleum is especially important because it has important and unique attributes leading to high economic utility that include very high energy density and transportability [20], massive availability, and relatively low price. Its future supply, however, is worrisome [21–23]. The issue is not the point between supply and potential demand. Barring a massive worldwide recession, demand will continue to increase, perhaps slowly, as human populations, petroleum-based agriculture, and economies (especially Asian) continue to grow. Petroleum supplies have been growing since 1900 at roughly four or five, but recently at two or one, percent per year. While most governments are trying to make their economies grow more rapidly, a trend many observers think is that high growth rates are unlikely to occur again anytime soon [23, 24]. Peak oil refers to the time at which an oil field, a nation, or the entire world reaches its maximum oil production and then declines. It is not some abstract issue debated by theoretical scientists or worried citizens but an actuality that occurred in the United States in 1970 and in some 60 (of 95) other oil-producing nations since [25–28]. Several prominent geologists have suggested that it may have occurred already for the world, although that is not clear yet, in part because the official statistics are including increasingly other liquid hydrocarbons such as natural gas liquids and biofuels under "oil" [29–31]. At some time, presumably, it will not be possible to continue to increase petroleum supplies or even to maintain current levels of supply, regardless of technology or price. At this point we will enter (or have entered) the "second half of the age of oil" [31]. The first half was one of year-by-year growth; the second half will be of year-by-year decline in supply, with possibly an "undulating plateau" around the peak. Natural gas will probably last a decade or two longer than oil as a major fuel source. We are of the opinion that it will not be possible to fill in the growing gap between supply and demand of conventional oil with alternatives on the scale required [32], and even were that possible, the investments in money, energy, and time required would mean that we needed to start some decades ago [33]. When or as the decline in global oil production begins, we will see the "end of cheap oil" and a very different economic climate.

The very large use of fossil fuels in the United States means that each of us has the equivalent of 60–80 hardworking laborers to "hew our wood and haul our water" as well as to grow, transport, and cook our food; make, transport, and import our consumer goods; and provide sophisticated medical and health services. Energy produced by these energy slaves even allows us to visit our relatives and take vacations in far away or even relatively nearby places. Simply to grow our food requires the energy of about a gallon of oil per person per day, and if a North American takes a hot shower in the morning, he or she will have already used far more energy than probably two-thirds of the Earth's human population use in an entire day.

19.3 How Much Oil Will We Be Able to Extract?

So the next important question is how much oil and gas are left in the world? The answer is a lot, although probably not a lot relative to our increasing needs and maybe not a lot of the high-quality stuff that we can afford economically or energetically. Although we will probably always have enough oil to lubricate our bicycle chains, the question is whether we will have anything like the quantity that we use now at the prices that allow the things we are used to having and whether growth is possible. Worldwide we have consumed about 1.3 trillion barrels of oil, mostly in the past 25 years. The current debate is fundamentally about whether there is 1, 2, or even 3.5 trillion barrels of economically extractable oil left. Fundamental to this debate, yet mostly ignored, is an understanding of the capital, operating and environmental costs, in terms of both money and energy, necessary to find, extract, and use whatever new sources of oil remain to be discovered and to generate whatever alternatives we might be able to develop. These investment issues, in terms of both money and energy, will become ever more important.

There are two distinct camps for this issue. One camp, the "technological cornucopians," led principally by economists such as Michael Lynch [34, 35], believes that market forces and technology will continue to supply (at a price) whatever oil we have a need for in the indefinite future. They argue that we now are able to extract only some 35% of the oil from a field, that large areas of the world (deep ocean, Greenland, Antarctica) have not been explored and may have substantial supplies of oil, and that substitutes, such as oil shale and tar sands, abound. They are buoyed by the failure of many earlier predictions of the demise or peak of oil production, two recent and prestigious analyses by the US Geological Survey and the Cambridge Energy Research Associates that tend to suggest that remaining extractable oil is near the high end given above, the recent discovery of the deepwater Jack 2 well in the Gulf of Mexico, and the development of the Alberta tar sands.

A second camp, the "peak oilers," is composed of scientists from diverse fields inspired by the pioneering work of M. King Hubbert [25], a few very knowledgeable politicians such as former U.S. congressman Roscoe Bartlett of Maryland, private citizens from all walks of life, and, increasingly, members of the investment community. Some of them come together once a year under the auspices of the International Society of BioPhysical Economics. All believe that there remains only about one additional trillion barrels of extractable conventional oil and that the global peak—or "bumpy plateau"—will occur soon or, perhaps, has already occurred (▣ Fig. 19.2). The arguments of these people and their organization, the Association for the Study of Peak Oil (ASPO), were spearheaded by the analyses and writings of geologists Colin Campbell and Jean Laherrere. They are supported by the many other geologists who agree with them, the many peaks that have already occurred for many dozens of oil-producing countries, the recent collapse of production from some of our most important oil fields, and that we now extract and use two to four barrels of oil for each new barrel discovered (▣ Fig. 8.3). They also believe that essentially all regions of the Earth favorable for oil production have been well explored for oil, and there are few surprises left except perhaps in regions that will be nearly impossible to exploit.

There are several issues that tend to add confusion to the issue of peak oil. First, some people do, and some do not, include natural gas liquids or condensate (liquid hydrocarbons that condense out of natural gas). These can be refined readily into motor fuel and other uses so that many investigators think they should simply be lumped with oil, which most usually they are. Since a peak in global natural gas production is thought to be likely one or two decades after a peak in global oil, inclusion of natural gas liquids extends the time or duration of whatever oil peak has occurred or may be occurring. The second is what characteristics of the peak will cause the largest economic impact? Is it the peak itself or the ratio between the declining production rate and the potential consumption rate? Both the production and the consumption of oil and also natural gas which had been growing at roughly 4% a year before 1970 declined gradually to 2% by 2005 and 1% or not at all since then. The great expansion of the economies of China and India has recently more than compensated for some reduced use in other parts of the world. Meanwhile the growth rate of the human population has continued so that "per capita peak oil" has probably occurred, perhaps as early as 1978 [36]. What the future holds possibly may have more to do with limiting carbon release than the declining physical production rate. Whenever we start on the inevitable downside of the global Hubbert curve, prices will rise.

The rates of oil and gas production (more accurately extraction) and the onset of peak oil are dependent upon interacting geological, economic, and political factors. The geological restrictions are the most absolute and depend on the number and physical capacity of the world's operating wells. In most fields the oil does not exist in the familiar liquid state but in what is more akin to a complex oil-soaked brick. The rate at which oil can flow through these "aquifers"

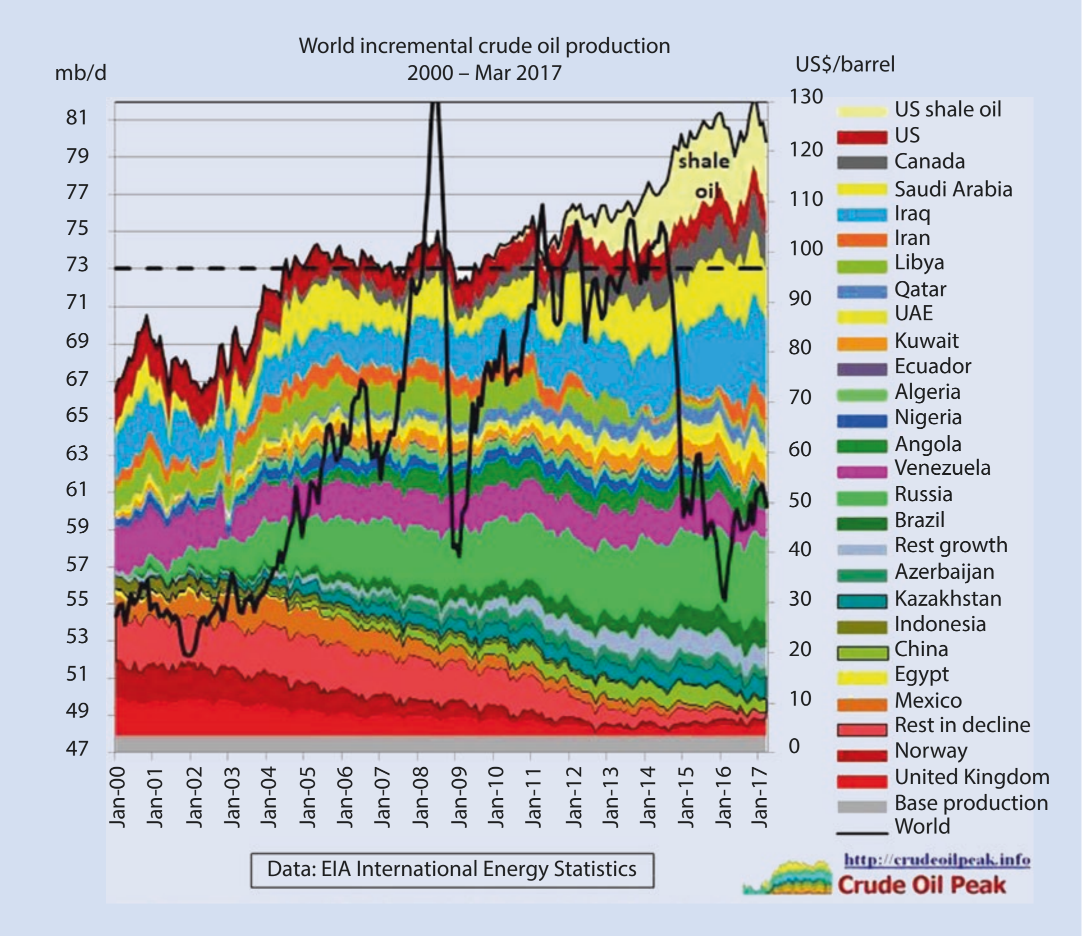


Fig. 19.2 Production of conventional oil in the world. This does not include recent additions of, e.g., natural gas liquids or biofuels to the data on "oil" but only conventional oil (Data source: Matt Mushalik)

depends principally upon the physical properties of the oil itself and of the geological substrate and upon the natural pressure forcing the oil through the substrate to the collecting wells. The natural pressures are increasingly replaced by pumping more gas or water into the structure. Detergents, CO_2, and steam can increase yields, but 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. The usual economic argument is that if supply is reduced relative to demand, then the price will increase which will then signal oil companies to drill more, leading to the discovery of more oil and then additional supply. Although that sounds logical, the empirical record shows that the rate at which oil and gas is found has little to do with the rate of drilling (Fig. 8.4). Recent experience may be changing that for "tight" oil and gas, where smaller amounts (compared to the past) of oil and gas can be obtained by drilling many low yielding wells.

Finally, output can be limited or (at least in the past) enhanced for political reasons—which are even more difficult to predict than the geological restrictions. Certainly the events of the "Arab spring" of 2011 were completely unpredictable. Empirically there is a fair amount of evidence from post-peak countries, such as the United States, that the physical limitations become important when about half of the ultimately recoverable oil has been extracted. But why should that be? In the United States, it certainly was not due to a lack of investment, since most geologists believe that the United States had been over-drilled. We probably will not know until we have much more data, and much of the data are closely guarded industry or state secrets. But whether or not the world has reached peak oil, most individual producing countries have [36, 37]. According to one analyst, if one looks at all of the 60 or so post-peak oil-producing countries, the peak occurs on average when about 54% of the total extractable oil in place has been extracted [37]. Finally oil-producing nations often have high population and economic growth and are using an increasing proportion of their own production, leaving less for export [38].

The United States clearly experienced “peak oil” in 1970 (although this might or might not be followed by a second peak based on unconventional oil about now; see ▸ Chapter 13). As the price of oil increased by a factor of 10, from 3.50 to 35 dollars a barrel during the 1970s, a huge amount of capital was invested in US oil discovery and production efforts. The drilling rate increased from 95 million feet per year in 1970 to 250 million feet in 1985. Nevertheless the production of crude oil decreased during the same period from the peak of 3.52 billion barrels a year in 1970 to 3.27 in 1985 and has continued to decline to 1.89 in 2005 even with the addition of Alaskan production. (There has been an upswing to a possible second peak in 2017). Natural gas production has also peaked and declined, although less dramatically. Thus despite the enormous advancement of petroleum discovery and production technology and despite very significant investment, US production of conventional oil has continued its downward trend nearly every year since 1970, and the US still imports nearly half the oil it uses. When drilling rates are high, apparently poorer prospects, on average, tend to be drilled. The technological optimists are correct in saying that advancing technology is important. But there are two fundamental and contradictory forces operating here, technological advances and depletion. In the US conventional oil industry, it is clear that depletion is trumping technological progress, as oil production is declining and oil is becoming much more expensive to produce. Because oil exploration and development is very energy intensive, it can lead to less net oil being delivered to society. As of 2017 there is a lot of drilling, and a lot of production, taking place, but even at prices high by historical standards, almost none of the oil companies are making a profit.

19.4 Decreasing Energy Return on Investment

Energy return on investment (EROI or EROEI) is simply the energy that one obtains from an activity compared to the energy it took to generate that energy. The calculations are generally straightforward, although the data may be difficult to get and the boundaries uncertain (see previous chapter). When the numerator and denominator are derived in the same units, as they should be (the units can be barrels per barrel, kcals per kcal, or MJoules per MJoule), the results are in a unitless ratio. The running average EROI for the *finding* of US conventional oil has dropped from greater than 300 kJ returned per kilojoule invested in 1919 to about five for one today. The EROI for *producing* that oil has declined from 30 to 1 in the 1970s to around ten for one today. This illustrates the decreasing energy returns as oil reservoirs are increasingly depleted and as there are increases in the energy costs as exploration and development are increasingly deeper and offshore [13, 21, 39]. Even that ratio reflects mostly pumping out oil fields that are half a century or more old since we are finding few significant new fields. A new, or newly analyzed, troubling trend is that the EROI for “elephants,” (i.e., the largest oil fields that still generate most of our oil), has been declining regularly in addition to their declining production [40]. The increasing energy cost of a marginal barrel of oil or gas is one of the factors behind their increasing dollar cost, although if one corrects for general inflation, the price of oil has increased only a moderate amount since 1970.

The same pattern of declining energy return on energy investment appears to be true for global petroleum production, but getting such information is very difficult. With help from the extensive financial database on “upstream” (i.e., preproduction) maintained by the John H. Herold Company, Gagnon and colleagues [41] were able to generate an approximate value for global EROI for producing new oil and natural gas (considered together). Their results indicate that the EROI for global oil and gas (at least for that which was publicly traded) was roughly 23:1 in 1992, increased to about 33:1 in 1999, and since then has fallen to approximately 18:1 in 2005. The apparent increase in EROI during the late 1990s reflects the effects of reduced drilling effort, as was seen for oil and gas in the United States (e.g., ▪ Figs. 19.3 and 19.4).

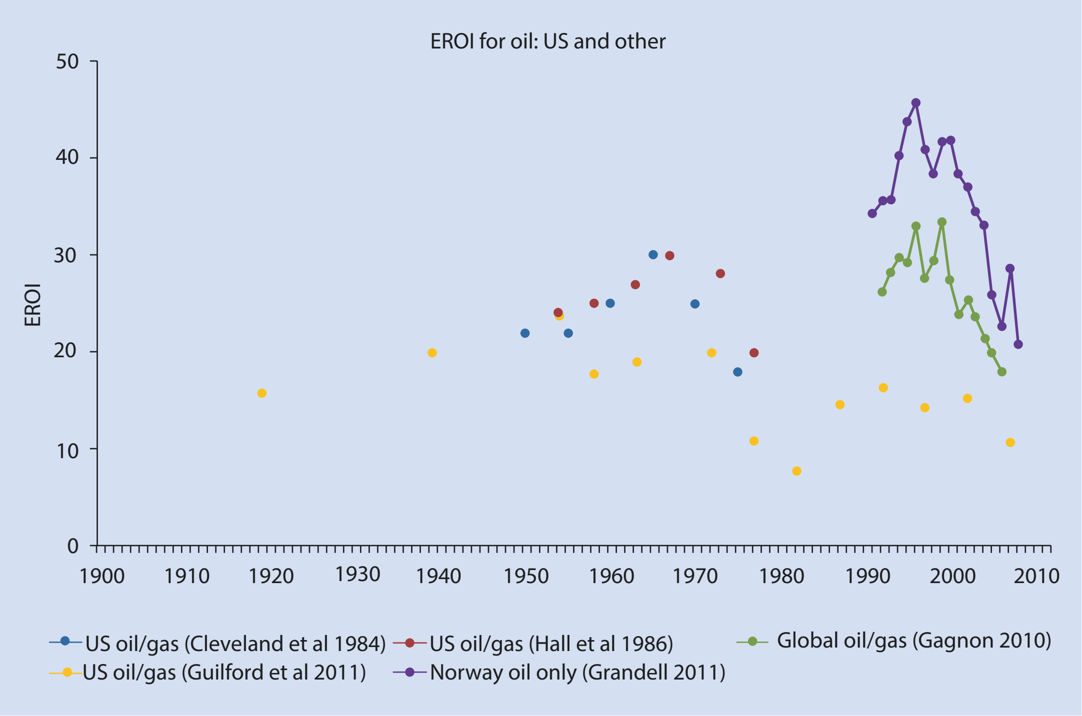


Fig. 19.3 EROI for oil and gas in the United States according to three more or less independent studies but all based on data from the US Bureau of Census (blue, yellow, and red dots: From Guilford et al. 2011). EROI for global publically traded companies (Green dots: From Gagnon et al. [41]. EROI for Norwegian oil: Grandell et al. 2011)

If the rate of decline continues linearly for several decades, eventually it would take the energy in a barrel of oil to get a new barrel of oil. While we do not know whether that extrapolation is accurate, essentially all EROI studies of our principal fossil fuels do indicate that their EROI is declining over time and that EROI declines especially rapidly with increased exploitation (e.g., drilling) rates. This decline appears to be reflected in economic results. In November of 2004, *The New York Times* reported that for the previous 3 years, oil exploration companies worldwide had spent more money in exploration than they had recovered in the dollar value of reserves found. The quantity of oil found in 2016 was only about 10% of the amount we produced and burned [42]. This illustrates that even though the EROI for producing oil and gas globally may still be about 15:1, it is possible that the energy breakeven point has been approached for finding new oil. Whether we have reached this point or not, the concept of EROI declining toward 1:1 makes irrelevant the reports of several oil analysts who believe that we may have substantially more oil left in the world. It simply does not make sense to extract oil, at least for fuel, when it requires more energy for the extraction than is found in the oil extracted.

How we weather this coming storm will depend in large part on how we manage our investments now. There are three general types of investments that we make in society. The first is investments into getting energy itself, the second is investments for maintenance of, and replacing, existing infrastructure, and the third is for discretionary expansion. In other words before we can think about expanding the economy, we must first make the investments into getting the energy necessary to operate the existing economy and also into maintaining the infrastructure that we have to compensate for the entropy-driven degradation of what we already have. The required investments into the second and especially the first category are likely to increasingly limit what is available for the third. The dollar and energy investments needed to get the energy needed to allow the rest of the

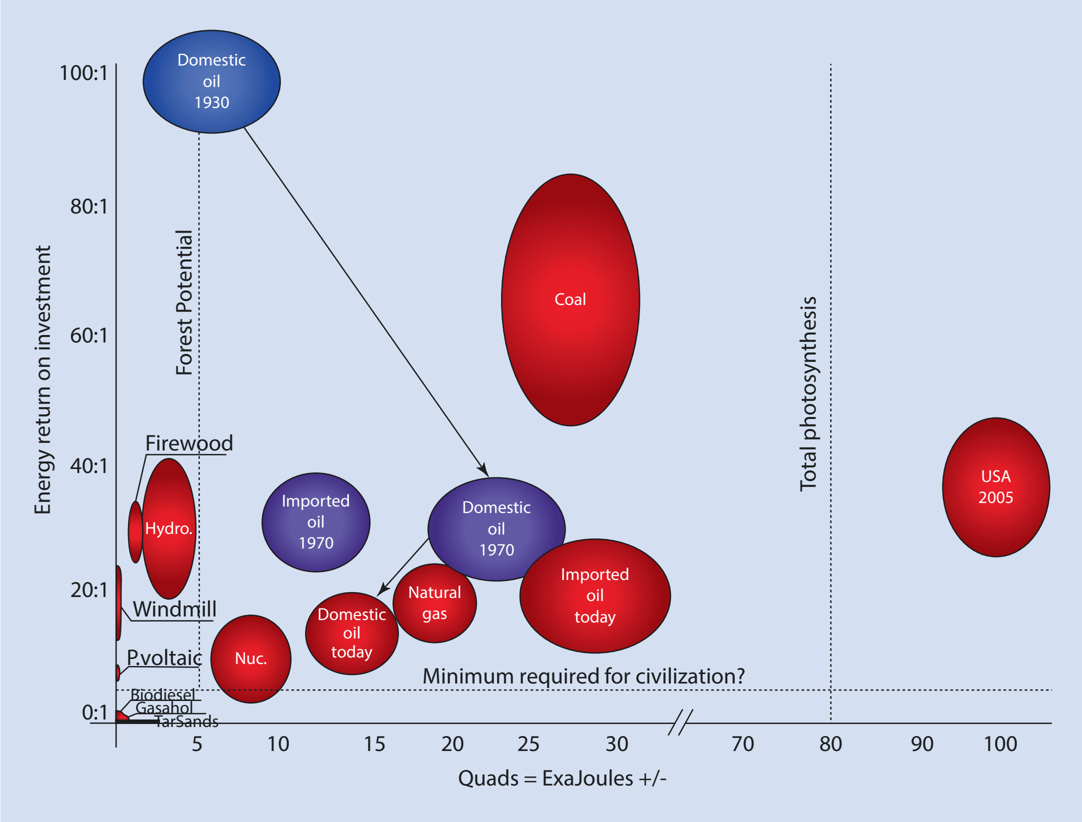


Fig. 19.4 "Balloon graph" representing quality (*y axis*) and quantity (*x axis*) for various fuels at various times in the US economy. *Arrows* connect fuels from various times (i.e., domestic oil in 1930, 1970, 2005), and the size of the "balloon" represents part of the uncertainty associated with EROI estimates (Source: US EIA, Cutler Cleveland and C. Hall's own EROI work). Note added in 2017: the high oil EROI value for 1930 represents the EROI for finding, not producing, oil and is slightly misleading although in a sense accurate. It might be better to use a value of 30:1 for 1970 which was the peak of EROI for production. See Guilford et al. (2011) for an update

economy to operate and grow have been very small historically, but this is likely to change dramatically. This is true whether we seek to continue our reliance on ever-scarcer petroleum or whether we attempt to develop some alternative. Technological improvements, if indeed they are possible, are extremely unlikely to bring back the low investments in energy that we have grown accustomed to.

The main problem that we face is a consequence of the "best first" principle. This is, quite simply, the characteristic of humans to use the highest-quality resources first, be they timber, fish, soil, copper ore, or fossil fuels. The economic incentives are to exploit the highest quality, least cost (both in terms of energy and dollars) resources first (as was noted by economist David Ricardo in 1891 [43]). We have been exploiting fossil fuels for a long time. The peak in finding new oil was in the 1930s for the United States and in the 1960s for the rest of the world. Both have declined enormously since then. An even greater decline has taken place in the efficiency with which we find oil, that is, the amount of energy that we find relative to the energy we invest in seeking and exploiting it.

That pattern of exploiting and depleting the best resources first also is occurring for natural gas. Natural gas was once considered a dangerous waste product of oil development and was flared at the well head. But during the middle years of the last century, large gas pipeline systems were developed in the United States and Europe that enabled gas to be sent to myriad users who appreciated its ease of use and cleanliness, including its relatively low carbon dioxide emissions, at least relative to coal [44]. US natural gas originally came from large fields, often associated with oil fields, in

Louisiana, Texas, and Oklahoma. Its production has moved increasingly to smaller fields distributed throughout Appalachia and the Rockies. A national peak in production occurred in 1973 as the largest fields that traditionally supplied the country peaked and declined. Later as "unconventional" fields were developed, a second, somewhat smaller peak occurred in the 2000s. Gas production had fallen by about 6% from that peak, and some investigators predict a "natural gas cliff" as conventional gas fields are increasingly exhausted and as it is increasingly difficult to bring smaller unconventional fields on line to replace the depleted giants. However, this "cliff" appears unlikely to occur for at least several decades because of the new technologies of horizontal drilling and hydrofracturing, which as of this writing are bringing in new "unconventional" gas at just about the rate that the conventional supplies are declining. It is quite difficult to predict the future of natural gas because of the many economic, environmental and social issues associated with horizontal drilling and hydraulic fracturing.

19.5 The Balloon Graph

All sources of energy used in the economy, except the free solar energy that drives ecosystem processes, have an energy cost, and all of them have different magnitudes of importance to society. The energy cost of obtaining coal or oil or photovoltaic electricity is straightforward even if difficult to calculate, but there are other sources and other ways payment is needed. For example, we pay for imported oil in energy as well as dollars, for it takes energy to grow, manufacture, or harvest what we sell abroad to gain the dollars with which we buy the oil (or we must in the future if we pay with debt today). In 1970 we gained roughly 30 mJ for each megajoule used to make the crops, jet airplanes, and so on that we exported [39]. But as the price of imported oil increased, the EROI of the imported oil declined. By 1974 that ratio had dropped to nine to one and by 1980 to three to one. The subsequent decline in the price of oil, aided by the inflation of the export products traded, eventually returned the energy terms of trade to something like it was in 1970, at least until the price of oil started to increase again after 2000, again lowering the EROI of imported oil. A rough estimate of the quantity used each year and the EROI of various major fuels in the United States, including possible alternatives, is given in ▣ Fig. 19.4. An obvious aspect of that graph is that qualitatively and quantitatively alternatives to fossil fuel have a very long way to go to fill the roles of fossil fuels. This is especially true when one considers the additional qualities of oil and gas, including energy density, ease of transport, and ease of use. The alternatives to oil available to us today are characterized by even lower EROIs, limiting their economic effectiveness. It is critical for CEOs and government officials to understand that the best oil and gas are simply gone, and there is no easy replacement.

If we are to supply into the future petroleum at the rate that the United States consumed in recent decades, let alone an increase, it will require enormous investments in either additional unconventional sources or payments to foreign suppliers. That will mean a diversion of the output of our economy from other uses into getting the same amount of energy just to run the existing economy. In other words, from a national perspective, investments will be needed increasingly just to run what we have, not to generate new real growth. If we do not make these investments, our energy supplies will falter, and if we do, the returns may be small to the nation, although the returns to the individual investor may be large. Further, if this issue is as important as we believe it is, then we must pay much more attention to the quality of the data we are getting about the energy costs of all things we do—including getting energy. Finally the failure of increased drilling to return more fuel (▣ Fig. 8.4) calls into question the basic economic assumption that scarcity-generated higher prices will resolve that scarcity by encouraging more production. Indeed scarcity encourages more exploration and development activity, but that activity does not necessarily generate more resources. Oil scarcity will also encourage the development of alternative liquid fuels, but their EROIs are generally very low.

19.6 Economic Impacts of Peak Oil and Decreasing EROI

Whether global peak oil has occurred already or will not occur for some years or, conceivably, decades, its economic implications will be enormous because we have no possible substitute on the scale required and at the EROI that is needed. Any alternatives will require enormous investments in money and energy when both are likely to be in short supply. Despite the projected impact on our economic and business life within relatively few years, neither government nor the business community is in any way prepared to deal with either the impacts of these changes or the new thinking needed for investment strategies. There are many reasons for this, but they include the role of economists in downplaying the importance of resources in the economy, the disinterest of the media, the failure of government to fund good analytic work on the various energy options, the erosion of good energy record keeping at the Departments of Commerce and Energy, and the focus of the media on trivial "silver bullets" despite the inability of any one of them (except economic contraction and in some few cases conservation) to contribute anything like 1% to the total energy mix.

Of perhaps greater concern is that none of the top ten or so energy analysts that we are familiar with are supported by government or, generally any, funding. There are not even targeted programs in the National Science Foundation or the Department of Energy where one might apply if one wishes to undertake good objective, peer-reviewed EROI analyses to see what options might actually be able to contribute significantly. Consequently much of what is written about energy is woefully misinformed or simply advocacy funded by various groups that hope to look good or profit from various perceived alternatives. Issues pertaining to the end of cheap petroleum will be the most important challenge that Western society has ever faced, especially when considered within the context of our need to deal simultaneously with climate change and other environmental issues related to energy. Any business or political leaders who do not understand the inevitability, seriousness, and implications of the end of cheap oil or who make poor decisions in an attempt to alleviate its impact are likely to be tremendously and negatively impacted as a result—and the rest of us with them. At the same time, the investment decisions we will make in the next decade or two will determine whether civilization is to make it through the transition away from petroleum or not.

What would be the impacts of a large increase in the energy and dollar cost of getting our petroleum or of any restriction in its availability? While it is extremely difficult to make any hard predictions, we do have the record of the impacts of the large oil price increases of the 1970s as a possible guide. These supply restrictions or "oil shocks" had very serious impacts on our economy which we have examined empirically in past publications [10]. At the time many economists did not think that even large increases in the price of energy would affect the economy dramatically because energy costs were but 3–6% of GDP. But by 1980, following the two "oil price shocks" of the 1970s, energy costs had increased dramatically until they were 14% of GDP. Actual shortages had additional impacts, when sufficient petroleum to run our industries or businesses were not available at any price. Other impacts included an exacerbation of our trade imbalances as more income was diverted overseas, adding to the foreign holdings of our debt and a decrease in discretionary disposable income as more money was diverted to access energy, whether via higher prices for imports, more petroleum exploration, or the development of low EROI alternative fuels. As EROI inevitably declines in the future, more and more of the economy's output will have to be diverted into getting the energy to run the economy. This in turn will affect those sectors of the economy that are not essential. Consumer discretionary spending will probably fall dramatically, greatly affecting nonessential businesses such as tourism and the economy more generally.

19.7 The "Cheese Slicer" Model

We have attempted to put together a conceptual and computer model to help us understand what might be the most basic implications of changing EROI on the economic activity of the United States. The model was conceptualized when we examined how the US economy responded to the "oil shocks" of the 1970s. The underlying foundation is the reality that the economy as a whole requires energy (and other natural resources derived from nature) to run, and without these most basic components, it will cease to function. The other premise of this model is that the economy as a whole is faced with choices in how to allocate its output in order to maintain itself and to do other things. Essentially the economy (and the collective decision-makers in that economy) has opportunity costs associated with each decision it makes. ▫ Figure 19.5 shows our basic

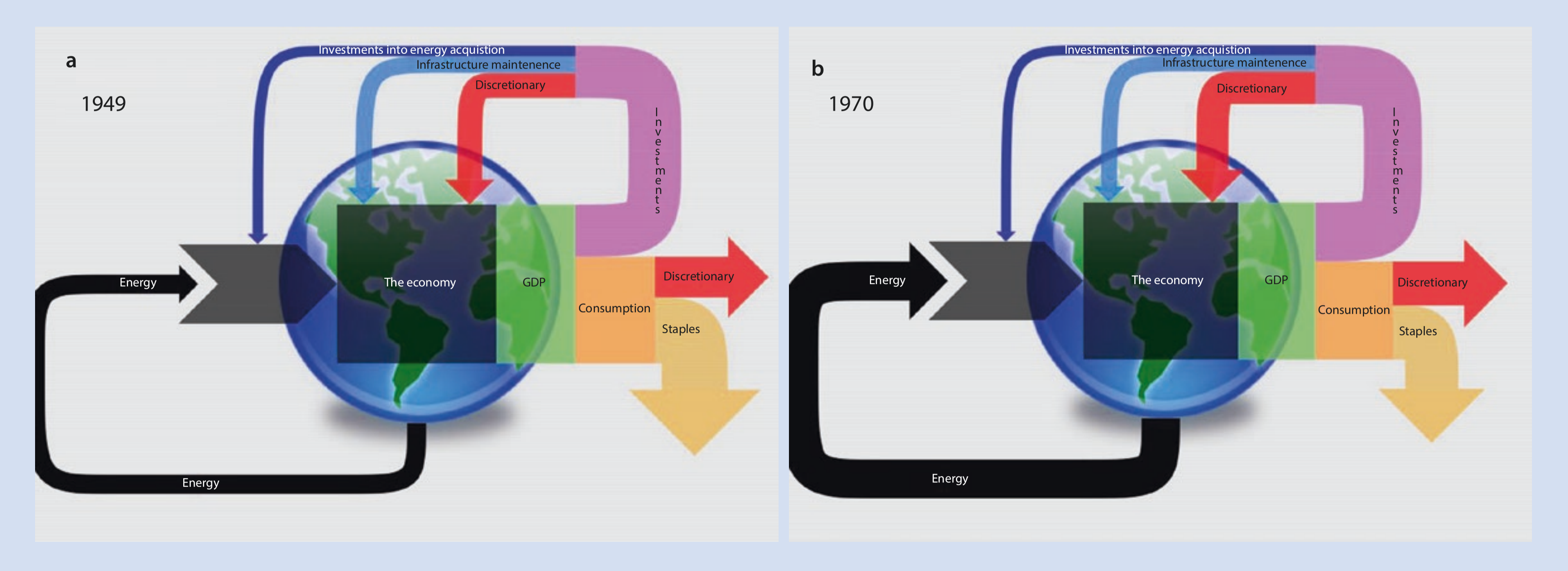


Fig. 19.5 The "cheese slicer" diagrammatic model (45), which is a basic representation of the fate of the output of the US economy (Source: U.S Department of Commerce & Andrea Bassi). **a** 1949 and **b** 1970. The *box* represents the US economy, the *input arrow* from the left represents the energy needed to run the economy, and the *large arrow* on the left of the box represents the output of the model (i.e., GDP) which is then subdivided as represented by the *output arrow* going to the right—i.e., first into investments (into getting energy, maintenance, and then discretionary) and then into consumption (either the basic required for minimal food, shelter, and clothing or discretionary). In other words the economic output is "sliced" into different uses according to the requirements and desires of that economy/society. **c** Same for **a** and **b** but for 1981, following large increases in the price of oil. Note change in discretionary investments. **d** Same for **a** and **b** but for 1990, following large increases in the price of oil. Note change in discretionary investments. **e** Same for **a** and **b** but for 2007, following large decreases then small increases in the price of oil. Note change in discretionary investments. **f** Same for **a** and **b** but projected for 2030, with a projection into the future with the assumption that the EROI declines from 20:1 (on average) to 10:1. **g** Same for **a** and **b** but projected for 2050, but a projection into the future with the assumption that the EROI declines to 5:1

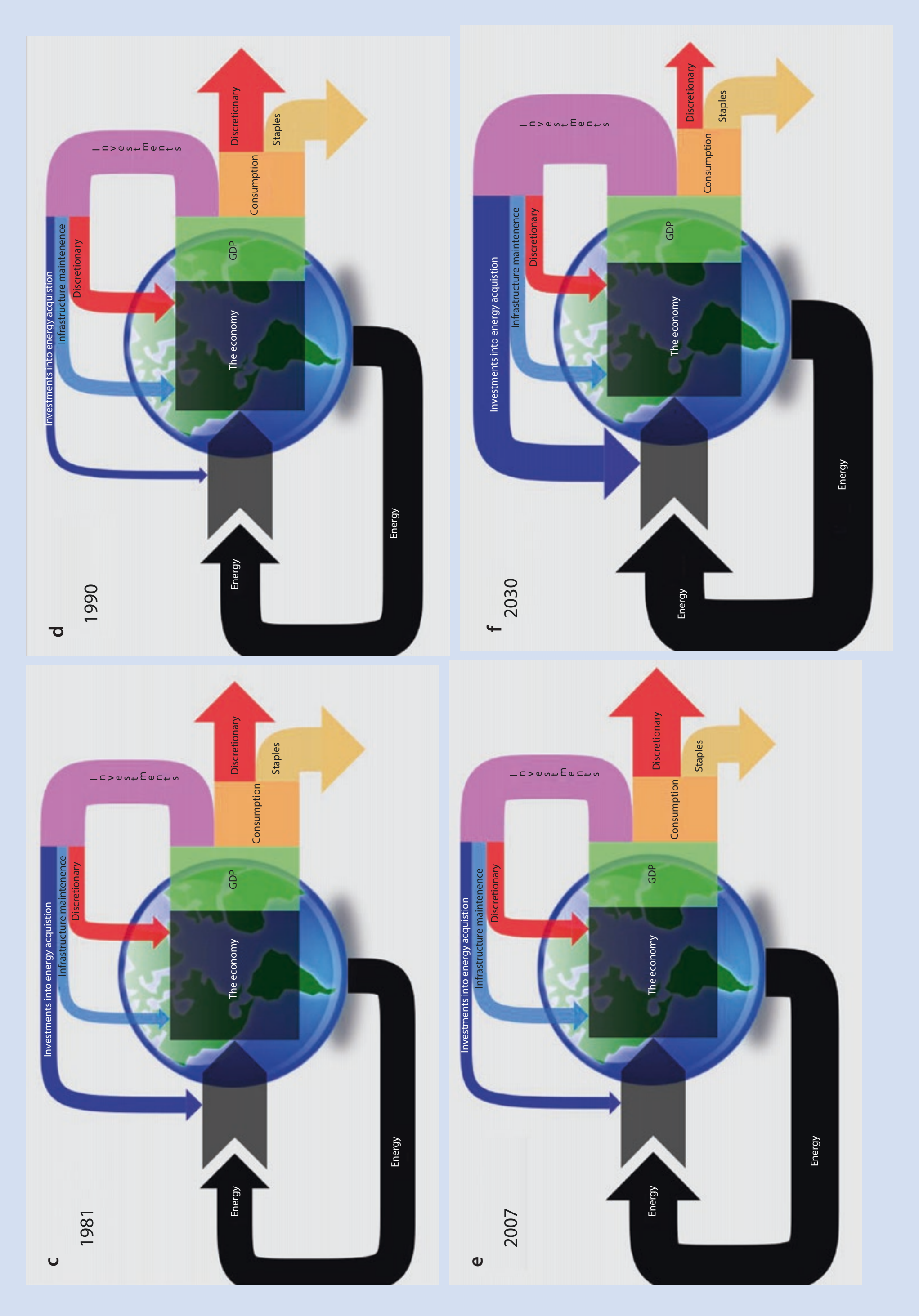
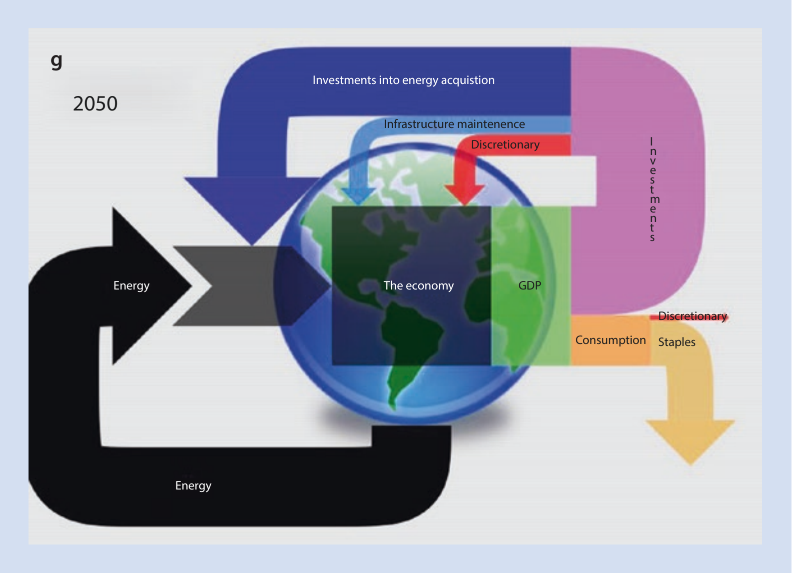


Fig. 19.5 (continued)

Fig. 19.5 (continued)



conceptual model parameterized for 1949 and 1970, before the oil shocks of that decade. The large square represents the structure of the economy as a whole, which we put inside a symbol of the Earth biosphere/geosphere to reflect the fact that the economy must operate within the biosphere [45]. In addition, of course, the economy must get energy and raw materials from *outside* the economy, that is, from nature (the biosphere/geosphere). The output of the economy, measured as GDP, is represented by the large arrow coming out of the right side, where the depth of the arrow represents 100% of GDP. For the sake of developing our concept, we think of the economy, for the moment, as an enormous dairy industry and cheese as the product coming out of the right-hand side, moving toward the right. This output (i.e., the entire arrow) could be represented as either money or embodied energy. We use money in this analysis but the results are probably not terribly different from using energy. So, our most important question is "how do we slice the cheese," that is, how do we, and how will we, divide up the output of the economy with the least objectionable opportunity cost. Most mainstream economists might answer "according to what the market decides," that is, according to consumer tastes and buying habits. But we want to think about it a little differently because we think things might be profoundly different in the future [43].

Most generally the output of the model (and the economy) has two destinations: *investment* or *consumption*. *Required* expenditures (without which the economy would cease to function) include (1) top line in blue are the investments into, or payments for, energy (i.e., the amount of economic output that is used to secure and purchase the domestic and imported energy needed for the economy), (2) investments in maintaining societal infrastructure (i.e., countering depreciation: repairing and rebuilding bridges, roads, machines, factories, vehicles—represented by the middle top arrow feeding back from output of the economy back to the economy itself), (3) some kind of minimal food, shelter, and clothing for the population (represented by the bottom rightward pointing arrow) required to maintain all individuals in society at the level of the federal minimum standard of living. This energy is absolutely critical for the economy to operate and must be paid for through proper payments and investments—which we consider together as investments to get energy. No investment in energy, no economic output. This "energy investment" feedback is represented by the topmost arrow from the output of the economy back upstream to the "workgate" symbol [44]. The width of this line represents the investment of energy into getting more energy. Of critical interest here is that as the EROI of our economy's total combined fuel source declines, then more and more of the output of the economy *must* be shunted back to getting the energy required to run the economy if the economy is to remain the same size.

Once these necessities are taken care of, what is left is considered the *discretionary* output of the economy. This can be either discretionary consumption (a vacation or a fancier meal, car, or house than needed, represented by the upper right pointing arrow in the diagrams) or discretionary investment (i.e., building a new tourist destination in Florida or the Caribbean, represented as the lower of the arrows feeding back into the economy). During the last 100 years, the vast wealth generated by the United States economy has meant that we have had an enormous amount of discretionary income. This is in large part because the expenditures for energy represented in ◻ Fig. 19.5 have been relatively small in the past.

The information needed to construct the above division of the economy is reasonably easy to come by for the US economy, at least if we are willing to make a few major assumptions and accept a fairly large margin of error. Inflation-corrected GDP, i.e., the size of the output of the economy, is published routinely by the US Bureau of Commerce. The total investments for maintenance in the US economy are available as "depreciation of fixed capital" (US Department of Commerce, various years). The minimum needed for food, shelter, and clothing is available as "personal consumption expenditures" (or the minimum of that required to be above poverty) which we selected from the US Department of Commerce for various years. The investment into energy acquisition is the sum of all of the capital costs in all of the energy-producing sectors of the United States plus expenditures for purchased foreign fuel. Empirical values for these components of the economy are plotted in ◻ Fig. 19.5. When these three requirements for maintaining the economy, investments and payments for energy, maintenance of infrastructure, and maintenance of people, are subtracted from the total GDP, then what is left is discretionary income.

We simulated two basic data streams: the US economy from 1949 to 1970 (representing the growth prior to the "oil crises" of 1973 and 1979) and the impact of the oil crisis and the recovery from that, which had occurred by the mid-1990s. Then we projected this data stream into the future by linearly extrapolating the data used prior to 2005 along with the assumption that the EROI for society declined from an average of roughly 20:1 in 2005 to 5:1 in 2050. This is an arbitrary scenario but may represent what we have in store for us as we enter the "second half of the age of oil," a time of declining availability and rising price when more and more of society's output needs to be diverted into the top arrow of ◻ Fig. 19.5.

19.8 Results of Simulation

The results of our simulation suggest that discretionary income, including both discretionary investments and discretionary consumption, will move from the present 50 or so percent in 2005 to about 10% by 2050 or whenever (or if) the composite EROI of all of our fuels reaches about 5:1 (◻ Figs. 19.5e and f).

19.9 Discussion

Individual businesses would be affected by increasing fuel costs and, for many, a reduction in demand for their products as people's income go increasingly for energy. This simultaneous inflation and recession happened in the 1970s and is projected to happen into the future as EROI for primary fuels declines. According to the economic theory called the Phillips Curve, the "stagflation" that occurred in the 1970s was not supposed to happen. According to Keynesian economics, inflation occurred only when the economy's aggregate demand exceeded its ability to produce. Unemployment was the result of too little aggregate demand. The simultaneous occurrence of inflation and unemployment rocked the very foundations of Keynesian analysis. But an energy-based explanation is easy [46]. As more money was diverted to getting the energy necessary to run the rest of the economy, disposable income and hence demand for many nonessentials declined, leading to economic stagnation. Meanwhile the increased cost for energy led to inflation, as no additional production occurred from higher prices. Unemployment increased during the 1970s but not as much as demand decreased, for at the margin labor became relatively useful compared to increasingly expensive energy. Individual sectors might be much more impacted as what happened in 2005, for example, with many Louisiana petrochemical companies that were forced to close or move overseas when the price of natural gas increased. On the other hand, alternate energy businesses, from forestry operations and woodcutting to solar devices, might do very well.

When the price of oil increases, it does not seem to be in national or corporate interest to invest in more energy-intensive consumption, as Ford Motor Company found out in 2008 with its former large emphasis on large SUVs and pickup trucks. (Although when energy prices declined again in 2016, big trucks came back!) When oil was cheap, we over-invested in remote second homes, cruise ships, and Caribbean semi-luxury hotels, so that we had a massive loss of the value of real estate. This was called the "Cancun effect"—such hotels require the existence of large amounts of disposable income from the US middle class and cheap energy. If EROI declines, that disposable energy may have to be shifted into the energy sector with an opportunity cost to the economy as a whole. Investors who understand the changing rules of the investment game are likely to do much better in the long run, but the consequence of having the "rug" of cheap oil pulled out from the economy will impact us for a long time.

So what can the scientist say to the investor? The options are not easy. As noted above worldwide investments in seeking oil have had very low returns in recent years. Investments in many alternatives have not fared much better. Ethanol from corn projects may be financially profitable to individual investors because they are highly subsidized by the government, but they are a very poor investment for the nation. It is not clear that ethanol makes much of an energy profit, with an EROI of 1.6 at best and less than one for one at worst, depending upon the study used for analysis [32, 47]. Biodiesel may have an EROI of about three to one. Is that a good investment? Clearly it is not relative to remaining petroleum. However real fuels must have EROIs of 5 or 10 or more returned on one invested to not be subsidized by petroleum or coal in many ways, such as the construction of the vehicles and roads that use them. Other biomass, such as wood, can have good EROIs when used as solid fuel but face real difficulties when converted to liquid fuels, and the technology is barely developed. The scale of the problem can be seen by the fact that we presently use several times more fossil energy in the United States than is fixed by all green plant production, including all of our croplands and all of our forests (Pimentel, D. Personal communication). Biomass fuels may make more sense in nations where biomass is very plentiful and, more importantly, where present use of petroleum is much less than in the United States. Alternatively, one might argue that if we could bring the use of liquid fuels in the United States down to, say, 20% of the present, then liquid fuels from biomass could fill in a substantial portion of that demand. We should remember that historically we in the United States have used energy to produce food and fiber, not the converse, because we have valued food and fiber more highly. Is this about to change?

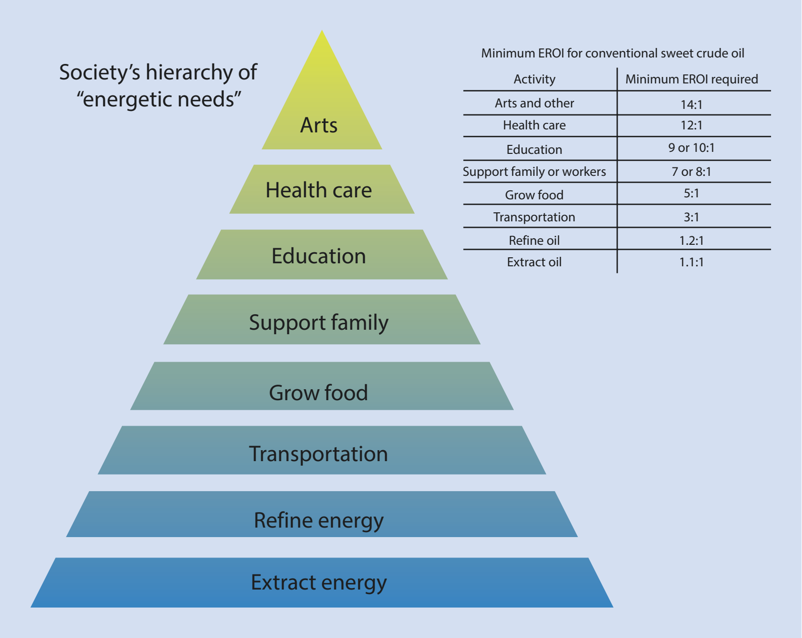
Energy return on investment from coal and possibly gas is presently quite large compared to alternatives (ranging from perhaps 50:1 to 100:1 at the point of extraction), but there is a large energy premium, perhaps enough to halve the EROI by the time they are delivered to society in a form that society finds acceptable. The environmental costs may be unacceptable, as may be the case for global warming and pollutants derived from coal burning. Injecting carbon dioxide into some underground reservoir seems unfeasible for all the coal plants we might build, but it is being pushed hard by many who promote coal. Nuclear has a debatable moderate energy return on investment (5–15:1, some unpublished studies say more). Newer analyses need to be made. Nuclear has a relatively small impact on the atmosphere, but there are large problems with public acceptance and perhaps safety in our increasingly difficult political world.

Wind turbines have an EROI of at least 15–20 returns on one invested, but this does not include the energy cost of backup or electricity "storage" for periods when the wind is not blowing. They make sense if they can be associated with nearby hydroelectric dams that can store water when the wind is blowing and release water when it is not, but the intermittent release of water can cause environmental problems. Photovoltaics are expensive in dollars and energy relative to their return, but the technology of both PV and storage is improving. One must be careful about accepting all claims for efficiency improvements because many require very expensive "rare-earth" doping materials, and some may become prohibitively expensive if their use expands greatly because of material shortages, even for copper [48, 49]. According to one savvy contractor, the efficiency in energy returned per square foot of collector has been increasing, but the energy returned per dollar invested has been constant as the price of the high-end units has increased. Additionally while photovoltaics have caught the public's eye, the return on dollar investment is about double for solar hot water installations. Wind turbines, photovoltaics, and some other forms of solar do seem to be a good choice if we are to protect the atmosphere, but the investment costs up front will be enormous compared to fossil fuels and the backup issue will be immense. Meanwhile the use of fossil fuel in the past decade has increased enormously relative to all of the solar.

Energy and money are not the only critical aspects of development of energy alternatives. Recent work by Hirsch and colleagues [33] has focused on the investments in time that might be needed to generate some kind of replacement for oil. They examined what they thought might be the leading alternatives to provide the United States with liquid fuel or lower liquid fuel use alternatives, including tar sands, oil shales, deepwater petroleum, biodiesel, high MPG automobiles and trucks, and so on. They assumed that these technologies would work (a bold assumption) and that an amount of investment capital equal to "many Manhattan projects" (the enormous project that built the first atomic bomb) would be available. They found that the critical resource was time. Once we decided to make up for the decline in oil availability, these projects would need to be started one or preferably two decades in advance of the peak to avoid severe dislocations to the US economy. Given our current petroleum dependence, the rather unattractive aspects of many of the available alternatives, and the long lead time required to change our energy strategy, the investment options are not obvious. This, we believe, may be the most important issue facing the United States at this time: where should we invest our remaining high-quality petroleum (and coal) with an eye toward insuring that we can meet the energy needs of the future. We do not believe that markets can solve this problem alone or perhaps at all. Research money for good energy analysis unconnected to this or that "solution" is simply not available.

Human history has been about the progressive development and use of ever higher-quality fuels, from human muscle power to draft animals to water power to coal to petroleum. Nuclear at one time seemed to be a continuation of that trend, but that is a hard argument to make today. Perhaps our major question is whether petroleum represents but one step in this continuing process of higher-quality fuel sources or rather is the highest-quality fuel we will ever have on a large scale. There are many possible candidates for the next main fuel, but few are both quantitatively and qualitatively attractive. In our view we cannot leave these decisions up to the market if we are to solve our future climate or peak oil problems. One possible way to look at the problem, probably not a very popular one with investors or governments, is to pass legislation that would limit energy investments to only "carbon-neutral" ones, remove subsidies from low EROI fuels such as corn-based ethanol, and then perhaps allow the market to sort from those possibilities that remain. Or should we generate a massive scientific effort, as objectively as possible, to evaluate all fuels and make recommendations?

A difficult decision would be whether we should subsidize certain "green" fuels. At the moment alcohol from corn is subsidized four times: in the natural gas for fertilizers, the corn itself through the Department of Agriculture's 100 or so billion dollar general program of farm subsidies, the additional 50 cents per liter subsidy for the alcohol itself, and a 50 cents per gallon tariff on imported alcohol. It seems pretty clear that the corn-based alcohol would not make it economically without these subsidies as it has only a marginal (if that) energy return. Are we in effect simply subsidizing the depletion of oil and natural gas (and soil) to generate an approximately equal amount of energy in the alcohol? We think so. Wind energy appears to have a relatively high EROI, enough to make it a reasonable candidate, although there are additional energy costs relative to backup technologies for when the wind is not blowing that have not been well calculated. So should wind be subsidized or allowed to compete with other "zero emission" energy sources? A question might be the degree to which the eventual market price would be determined by, or at least be consistent with, the EROI, as all the energy inputs (including that to support labor's paychecks) must be part of the costs. Otherwise that energy is being subsidized by the dominant fuels used by society.



Minimum EROI for conventional sweet crude oil

Activity	Minimum EROI required
Arts and other	14:1
Health care	12:1
Education	9 or 10:1
Support family or workers	7 or 8:1
Grow food	5:1
Transportation	3:1
Refine oil	1.2:1
Extract oil	1.1:1

▪ **Fig. 19.6** "EROI pyramid" of increasing abilities to support economic activities as a function of the mean EROI of a society. The values run from 1.1:1 to extract energy to 3:1 to provide transportation, etc. to perhaps 12 or 15:1 to provide for the complex amenities of civilization. Values up through transportation are based on Hall et al. 2008 and are fairly solid; higher values are increasingly speculative quantitatively. Graph from Lambert et al. (2014) as inspired by Maslow's pyramid of human needs

19.10 What Level EROI Do We Need?

We have stated that the criteria used by some investigators for an "acceptable" EROI has been only that it is positive, i.e., above one return for one invested. But in fact, as we developed in the last chapter, we need at least 3:1 to drive a truck if we include the cost of getting the fuel to the truck and pay for the depreciation of the infrastructure to use it. But we need also to pay for the "depreciation" of the workers as well, meaning the energy required to educate his or her children, provide for health care, and in general support the family, not to mention the various cultural amenities that make life good. We have developed this concept in some detail elsewhere [50] but provide a summary as ▪ Fig. 19.6.

19.11 Conclusion

It seems obvious to us that the US economy is very vulnerable to a decreasing EROI for its principle fuels. Increasing impacts will come from an increase in expenditures overseas as the price of imported oil increases more rapidly than that of the things that we trade for it, from increased costs for domestic oil and gas as reserves are exhausted and new reservoirs become increasingly difficult to find and as we turn to lower EROI alternatives such as biodiesel and/or photovoltaics. Our "cheese slicer" model suggests that as economic requirements for getting energy increase, a principal effect will be a decline in discretionary income as a proportion of GDP. Since more fuel will be required to run the same amount of economic activity, the potential for increased environmental impacts is very strong. On the other hand, protecting the environment, which we support strongly, may mean turning away from some higher EROI fuels to some lower ones. We think all of these issues are very important yet are hardly discussed objectively in our society or even in economic or scientific circles.

? Questions

1. What was the experience of Cuba that allows us to understand better the role of energy in an economy?
2. What is meant by the phrase "the second half of the age of oil"?
3. Argue for or against the following question: the important issue is "when will we run out of petroleum."
4. How much oil do we discover for each barrel that we burn?
5. What happens to pressure as an oil field matures? Why?
6. What is the "cheese slicer" model?

7. Explain the difference between investment and consumption?
8. What is discretionary consumption?
9. What is the "Cancun effect"?
10. What resource does Hirsch and his colleagues think is especially important to adjust to a post-peak oil society?

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References

1. Hall, Charles A.S., Robert C. Powers, and William Schoenberg. 2008. Peak oil, EROI, investments and the economy in an uncertain future. In *Renewable energy systems: Environmental and energetic issues*, ed. D. Pimentel, 113–136. London: Elsevier.
2. Soddy, F. 1926. *Wealth, virtual wealth and debt*. New York: E.P. Dutton and Co.
3. Tryon, F.G. 1927. An index of consumption of fuels and water power. *Journal of the American Statistical Association* 22: 271–282.
4. Cottrell, F. 1955. *Energy and society*. Dutton: Greenwood Press.
5. Georgescu-Roegen, N. 1971. *The entropy law and the economic process*. Cambridge: Harvard University Press.
6. Odum, H.T. 1972. *Environment, power and society*. New York: Wiley-Interscience.
7. Kümmel, R. 1982. The impact of energy on industrial growth. *Energy – The International Journal* 7: 189–203.
8. ———. 1989. Energy as a factor of production and entropy as a pollution indicator in macroeconomic modelling. *Ecological Economics* 1: 161–180.
9. Jorgenson, D.W. 1984. The role of energy in productivity growth. *The American Economic Review* 74 (2): 26–30.
10. ———. 1988. Productivity and economic growth in Japan and the United States. *The American Economic Review* 78: 217–222.
11. Daly, H.E. 1977. *Steady-state economics*. San Francisco: W. H. Freeman.
12. Dung, T.H. 1992. Consumption, production and technological progress: A unified entropic approach. *Ecological Economics* 6: 195–210.
13. Hall, C.A.S., C.J. Cleveland, and R.K. Kaufmann. 1986. *Energy and resource quality: The ecology of the economic process*. New York: Wiley-Interscience.
14. Ayres, R.U. 1996. Limits to the growth paradigm. *Ecological Economics* 19: 117–134.
15. Ayres, Robert U., and Benjamin Warr. 2009. *The economic growth engine: How energy and work drive material prosperity*. Northhampton Mass: Edward Elger.
16. Quinn, M. 2006. The power of community: How Cuba survived peak oil. Text and film. Published on 25 Feb 2006 by Permaculture Activist. Archived on 25 Feb 2006. Can be reached at megan@communitysolution.org.
17. Kaufmann, R. 2004. The mechanisms for autonomous energy efficiency increases: A cointegration analysis of the US energy/GDP ratio. *The Energy Journal* 25: 63–86.
18. Hall, C.A.S., and J.Y. Ko. 2006. The myth of efficiency through market economics: A biophysical analysis of tropical economies, especially with respect to energy, forests and water. In *Forests, water and people in the humid tropics: Past, present and future hydrological research for integrated land and water management*, ed. M. Bonnell and L.A. Bruijnzeel, 40–58. Cambridge University Press: UNESCO.
19. LeClerc, Grégoire, and C.A.S. Hall, eds. 2006. *Making world development work: Scientific alternatives to neoclassical economic theory*. Albuquerque: University of New Mexico Press.
20. Smil, V. 2007. Light behind the fall: Japan's electricity consumption, the environment, and economic growth. *Japan Focus*, April 2; EIA. (2009). U.S. Energy Information Agency website. Accessed June 2009.
21. Cleveland, C.J. 2005. Net energy from the extraction of oil and gas in the United States. *Energy*. *The International Journal* 30 (5): 769–782.
22. Campbell, C., and J. Laherrere. 1998. The end of cheap oil. *Scientific American* (March): 78–83.
23. Heinberg, R. 2003. *The Party's over: Oil, war and the fate of industrial societies*. Gabriella Island, B.C. Canada: New Society Publishers.
24. Galbraith, J. K. 2014. The end of normal. Simon and Shuster, N.Y.
25. Hubbert, M.K. 1969. Energy resources. In *Resources and man*. National Academy of Sciences, 157–242. San Francisco: W.H. Freeman.
26. Strahan, D. 2007. *The last oil shock: A survival guide to the imminent extinction of petroleum man*. London: Hachette Publisher.
27. Energyfiles.com. Accessed August 2007. www.energyfiles.com.
28. Deffeyes, K. 2005. *Beyond oil: The view from Hubbert's peak*. New York: Farrar, Straus and Giroux.
29. EIA. 2007. U.S. Energy Information Agency website. Accessed June 2007.
30. IEA. 2007. European Energy Agency, web page. Accessed August 2007.
31. Campbell, C. 2005. *The 2nd half of the age of oil*. Paper presented at the 5th ASPO Conference, Lisbon Portugal. See also. In *The first half of the age of oil: An exploration of the work of Colin Campbell and Jean Laherrere*, ed. C.A.S. Hall and R.C. Pascualli. New York: Springer. 2012.

32. Murphy, D.J., C.A.S. Hall, and Bobby Powers. 2011. New perspectives on the energy return on investment of corn based ethanol. *Environment, Development and Sustainability* 13 (1): 179–202.
33. Hirsch, R., Bezdec, R. and Wending, R. 2005. Peaking of world oil production: Impacts, mitigation and risk management. U.S. Department of Energy. National Energy Technology Laboratory. Unpublished Report.
34. Lynch, M.C. 1996. The analysis and forecasting of petroleum supply: Sources of error and bias. In *Energy watchers VII*, ed. D.H.E. Mallakh. Boulder: International Research Center for Energy and Economic Development.
35. Adelman, M.A., and M.C. Lynch. 1997. Fixed view of resource limits creates undue pessimism. *Oil and Gas Journal* 95: 56–60.
36. Duncan, R.C. 2000. *Peak oil production and the road to the Olduvai Gorge*. Keynote paper presented at the Pardee Keynote Symposia. Geological Society of America, Summit 2000.
37. Brandt, A.R. 2007. Testing Hubbert. *Energy Policy* 35: 3074–3088.
38. Hallock, J., P. Tharkan, C. Hall, M. Jefferson, and W. Wu. 2004. Forecasting the limits to the availability and diversity of global conventional oil supplies. *Energy* 29: 1673–1696; Hallock, J., Jr., W. Wu, C.A.S. Hall, and M. Jefferson. 2014. Forecasting the limits to the availability and diversity of global conventional oil supply: Validation. *Energy* 64: 130–153.
39. Cleveland, C.J., R. Costanza, C.A.S. Hall, and R.K. Kaufmann. 1984. Energy and the US economy: A biophysical perspective. *Science* 225: 890–897.
40. Musnadi, M., and A. Brandt. 2017. Energetic productivity dynamics of global super-giant oilfields. *Energy and Environmental Science* 10: 1493–1504.
41. Gagnon, N., C.A.S. Hall, and L. Brinker. 2009. A preliminary investigation of energy return on energy investment for global oil and gas production. *Energies* 2 (3): 490–503.
42. Holter, M. 2016. Oil discoveries at a 70 year low signal supply shortfall ahead. Bloomberg The year ahead. August 30.
43. Ricardo, David. 1891. *The principles of political economy and taxation*. London: G. Bell and Sons. (Reprint of 3rd edition, originally pub 1821).
44. Hughes, D. 2011. Will natural gas fuel America in the 21st century? Post Carbon Institute. There are a number of other very good reports on oil and gas resources by Hughes available from the Post Carbon Institute.
45. Odum, H.T. 1994. *Ecological and general systems: An introduction to systems ecology*. Niwot: University Press of Colorado. Millennium Institute. 2007. Data principally from the U.S. Department of Commerce. Extrapolations via the Millennium Institute's T-21 model courtesy of Andrea Bassi.
46. Hall, C., D. Lindenberger, R. Kummel, T. Kroeger, and W. Eichhorn. 2001. The need to reintegrate the natural sciences with economics. *Bioscience* 51: 663–673; Hall, C.A.S. 1992. Economic development or developing economics? In *Ecosystem rehabilitation in theory and practice, Vol I. Policy issues,* ed. M. Wali, 101–126. The Hague, Netherlands: SPB Publishing.
47. Farrell, A.E., R.J. Plevin, B.T. Turner, A.D. Jones, M. O'Hare, and D.M. Kammen. 2006. Ethanol can contribute to energy and environmental goals. *Science* 311 (5760): 506–508. and also the many letters on that article in Science Magazine, June 23, 2006.
48. Andersson, B.A., C. Azar, J. Holmerg, and S. Karlsson. 1998. Material constraints for thin-film solar cells. *Energy* 23: 407–411.
49. Gupta, A.J. in press. *Materials: Abundance, purification, and the energy cost associated with the manufacture of Si, CdTe, and CIGS PV*. Amsterdam: Elsevier.
50. Lambert, J., C.A.S. Hall, S. Balogh, A. Gupta, and M. Arnold. 2014. Energy, EROI and quality of life. *Energy Policy* 64: 153–167.