The Methane Age

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methane-related technologies noted above. The (possible) shift from a petroleum-dominated global fuel system to a methane-dominated system would surely have profound worldwide geopolitical, balance-of-payments, defense and security related, and industrial–structural impacts. We have not yet even identified some primary and many secondary effects.

These preliminary results of IIASA analyses, and the Institute's continuing research interests in energy, technology, and environmental policy issues, culminated in a workshop, held in Sopron, Hungary, involving invited specialists from both East and West, in May 1986. The primary purpose of this high-level, but informal, meeting was to question, criticize, expand, and test IIASA's background hypotheses and other promising research to date. A secondary objective was to identify potentially rewarding issues for further analysis. To what extent we managed to achieve our objectives the reader may judge from this book, based in large part on the selected and edited workshop proceedings.

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CHAPTER 2

The Dynamic Evolution of Methane Technologies

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2.1. Introduction

The use of natural gas has been increasing in many parts of the world, especially in most industrialized countries. As a result, natural gas has emerged as one of the three most important sources of energy, ranking third in the world after oil and coal, while in the USA it is second only to oil. Despite enormous increases in natural gas consumption and related improvements in production, transport, conversion, distribution, and end-use technologies, natural gas is still considered the "stepchild" of the oil industry – a by-product of oil production.

This is the more surprising considering the promising prospects for the widespread use of natural gas in the future. Natural gas is cleaner than any other fossil energy source, and unlike other fossil energy forms, produces limited particulate and sulfur emissions that can be even further reduced by relatively simple measures. In the past, most natural gas discoveries were incidental to oil prospecting. Today, there is increasing evidence that methane may be more abundant and distributed more evenly throughout the world than other fossil energy sources. In fact, estimates of natural gas resources have increased substantially during the last decade. However, despite decisive environmental advantages and a potentially abundant supply, the use of natural gas stagnated during recent years. The gas bubble still persists because acquiring new markets turned out to be more difficult than had been anticipated by the promoters of natural gas during the phase of rapid growth that lasted until a few years ago.

Our contention is that most of the difficulties encountered in attempts to increase the use of natural gas could be resolved if specific technologies were to be developed that are tailored to natural gas and are not mere derivatives of oil technologies. In other words, a prerequisite for the widespread use of natural gas in the future is the increasing decoupling of methane technologies from oil technologies. As a consequence, the oil and gas industry would eventually split into two separate entities. Before embarking on the justification of our contention, we first describe the evolution of the energy system and the dynamics of natural gas. With this historical perspective, we then outline the future developments likely to lead to the separation of the oil and gas industry, and of oil and methane technologies.

2.2. Primary Energy Consumption

At the beginning of the nineteenth century, the primary energy inputs were fuel wood, agricultural wastes, and mechanical wind and water power, in addition to animal and human muscle power. Poor as this may be, by present standards, it represents a sophisticated system compared to earlier practices. A considerable infrastructure of canals and roads was already in place for timber transport; mining and manufacturing were usually associated with elaborate systems of dams and water-wheels; thus, motive and shaft power came from draft animals and hydraulic systems, and heat from biomass. In primary energy terms, fuel wood represented most of the energy inputs.

Figure 2.1 (Nakicenovic, 1984) shows primary energy consumption in the world since 1860. The data are plotted on a logarithmic scale and show exponential growth phases in consumption of the most important sources of primary energy during the last 130 years in piecewise linear secular trends. Consumption of fuel wood, once the most important source of energy, has declined since the beginning of the century, although its use is still widespread, especially in the developing parts of the world. With the expansion of railroads and the steel industry and the application of steam in general, coal use increased exponentially until the 1910s and has oscillated ever since with an overall lower average growth rate. Both oil and natural gas were introduced during the 1870s, and their consumption has increased, with even more rapid exponential growth rates ever since. In fact, the oil and natural gas curves have the same shape and almost identical growth rates; they are just shifted in time by about 10 to 15 years. Oil and natural gas use grew in parallel with the petrochemical industry, the electricity and electrical industry, internal combustion and electric prime movers. Nuclear energy is still in its early phase of development; therefore the steep growth rates prevailing over the last decade may not be indicative of its future role. During recent years, the growth of nuclear energy has declined worldwide to more moderate rates.

Thus, during this 130-year period, energy consumption did not draw equally from all sources, nor did the use of all energy sources increase equally. Yet, global primary energy consumption (including fuel wood) grew exponentially at an average rate of 2.3% per year. It is evident that the

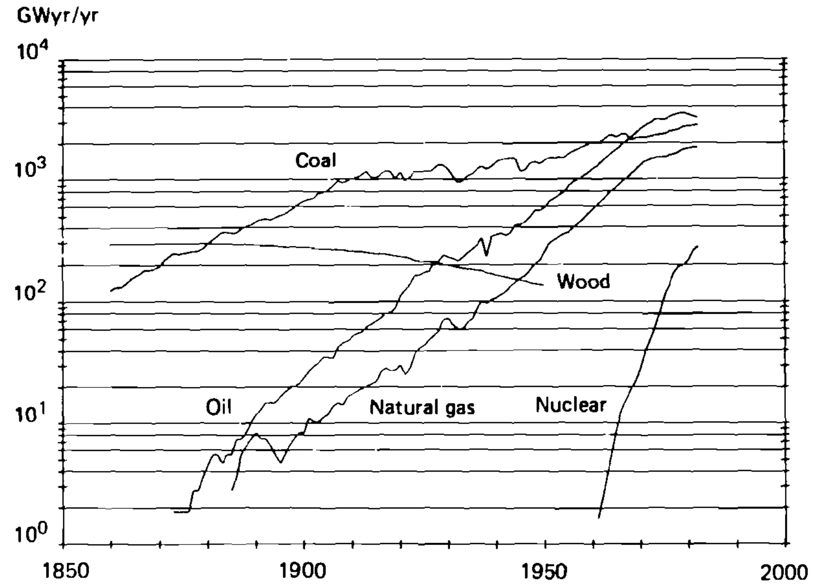

Figure 2.1. World primary energy consumption.

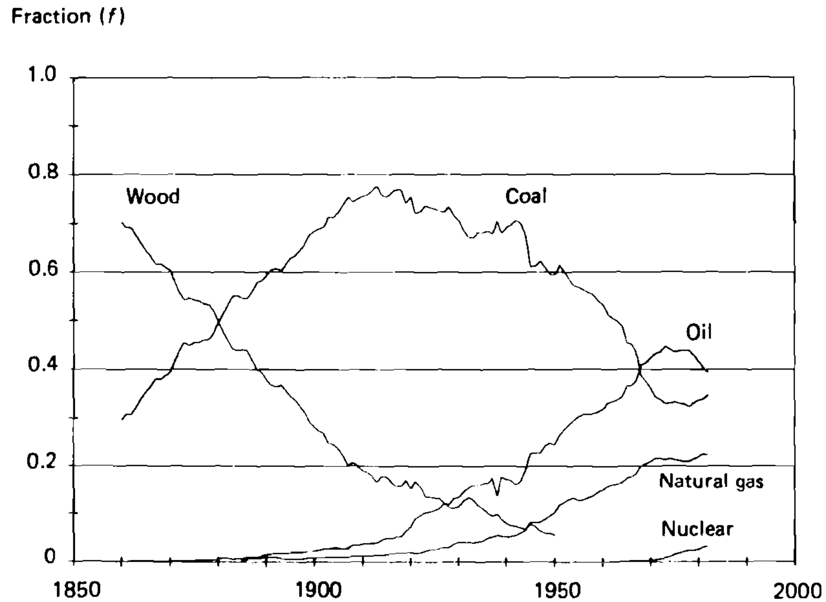

Figure 2.2. World fractional shares of major primary energy sources.

older forms of energy have been replaced by new ones. Thus, the decline of the older energy sources was compensated by the more rapid growth of the new ones. These dynamic changes are clearly seen in *Figure 2.2* (Nakicenovic, 1984), which shows the fractional market shares of the five most important primary energy sources taken from *Figure 2.1*. In terms of fractional market shares, coal had already replaced fuel wood during the last half of the nineteenth century. In 1860, fuel wood supplied about 70% of consumed energy, but by the 1900s its share had dwindled to little more than 20%. Owing to the insignificant use of crude oil and natural gas during the last century, most of the market share losses incurred by fuel wood were caused by the rapid increases of coal's share of primary energy – from 30% in 1860 to almost 80% by the 1900s. By 1910, the rapid increase in coal use had ceased, and during the 1920s, a phase of decline set in. This decline in the relative share of coal use resembles the market losses of fuel wood 50 years earlier. The replication of this pattern is almost symmetrical because, after the 1920s, both fuel wood and coal were replaced by still newer sources of energy – crude oil and natural gas.

2.3. Natural Gas in the Global Context

The evolution of primary energy use, viewed as a technological substitution process, is shown in *Figure 2.3* (Nakicenovic, 1984) on a logarithmic plot of the fractional market shares of the five primary energy sources (from *Figure 2.2*). The fractional shares (f) are not plotted directly, but rather as the quantity $f/(1-f)$ that transforms the logistic curve into a straight line (i.e., as the linear transformation of the logistic function). The quantity is the ratio of the market share taken by a given energy source over the sum of the market shares of all other competing energy sources. This form of presentation reveals the logistic substitution path as an almost linear secular trend with small annual perturbations. Thus, the presence of linear trends in *Figure 2.3* indicates where the fractional substitution of energy sources follows a logistic curve.

The model estimates of the substitution process are extended beyond the historical period up the the year 2050 [1]. For such an explorative "look" into the future, additional assumptions are required because potential new competitors, such as nuclear and solar energy, have not captured sufficient market shares in the past to allow estimation of their penetration rates. We have assumed a more modest nuclear penetration rate that resembles the historical growth rates of the introduction of coal, crude oil, and natural gas into the energy system. The nuclear scenario, therefore, prescribes a 1% share in 1965, and a 3% share 25 years later in 1990 (in 1982, the nuclear share in global primary energy consumption was 3.5%). For the next energy source, which we symbolically call "solfus" to indicate the potential use of both solar and fusion energy, we have postulated an equivalent scenario with a 1% share in the year 2025, rising to 3% in 2050.

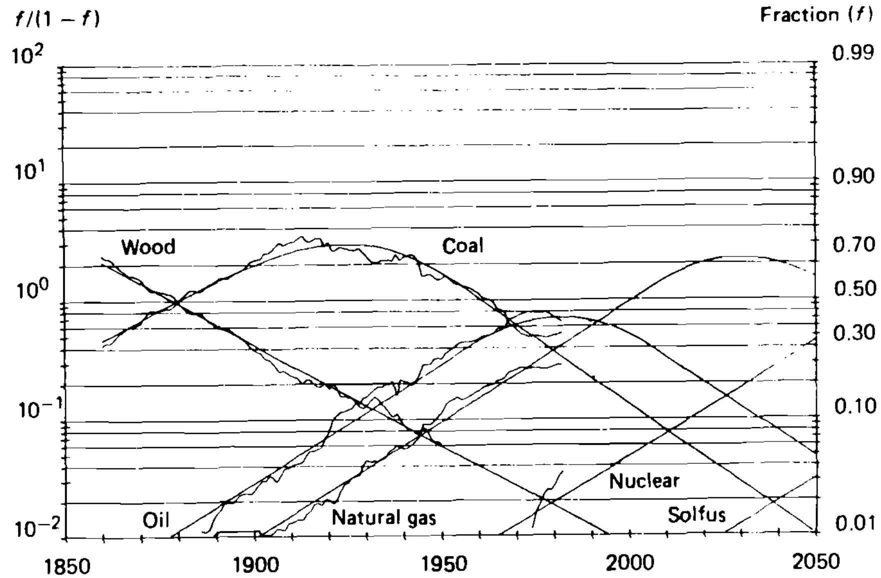

Figure 2.3. World primary energy substitution (with projections).

These two assumptions, together with the dynamics of energy substitution prescribed by past events, describe the resulting evolution of the global energy system throughout the first half of the next century.

The prominent feature in this projection of primary energy substitution dynamics into the future is the emergence of natural gas as the dominant energy source during the next decades. According to *Figure 2.3*, more than half of all the primary energy consumed globally will be natural gas after the end of this century. This result illustrates that not only would the natural gas bubble be absorbed in a few years, but that methane technologies would develop in the future, creating new growth sectors. Although this result is unexpected in terms of the numerous energy debates of the last 10 to 15 years, it is perhaps reassuring that we may not, after all, have to rely on nuclear or alternative energy sources for another 50 years or so. Instead, the possible future that emerges would require less radical changes, but we still face a challenging task to develop new technologies and to improve the performance of those already employed, such as deep drilling, pipelines, and methane conversion into other energy carriers (e.g., electricity and methanol). Despite the current difficulties involved in expanding the use of natural gas in a time of worldwide economic slowdown and low energy (i.e., crude oil) prices, our scenario paints a different picture, albeit only in the long run.

To gain a better understanding of how such changes may come about, we will first investigate the history of natural gas in greater depth. Thereafter, we return to the broader picture of primary energy and the creation of the new growth sectors that could emerge from expanding methane technologies and their use.

Figure 2.4 shows the history of natural gas production for the world. The shares of the four most important producing regions are plotted since 1900. North America (the USA and Canada) was the dominant producer of natural gas until 1983, being superseded by the Soviet Union during the subsequent three years. In fact, the USA has produced most of the natural gas ever extracted globally, and still continued to produce more than half until the mid-1970s. The history of natural gas is, therefore, closely linked to the USA.

Figure 2.4 also shows the model estimates of the actual market shares of the four major producing regions, but they are included for illustrative purposes only and are not intended to indicate likely future development. Rather, they indicate that the actual market shares of the four producing regions fluctuated widely away from the model estimates, especially from World War II through the 1960s. However, the historical trend away from North American dominance and toward a more widely distributed natural gas production throughout the world should continue, and this is one of the

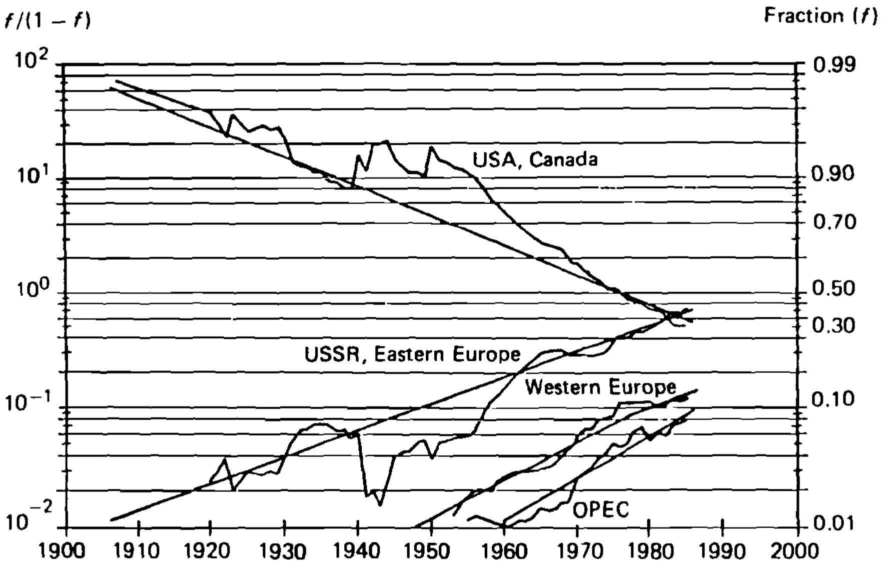

Figure 2.4. World natural gas production by major regions. (Note that the residual to total world production was not plotted. Therefore, market shares do not add to 100%.)

crucial issues associated with the future use of natural gas to which we will return. However, we will next analyze the evolution of the natural gas industry in the USA, since it has been the dominant producer and still is the largest consumer of natural gas, and because US data are readily available.

2.4. Natural Gas in the USA

The USA has a longer recorded history of primary energy use than anywhere else in the world. *Figure 2.5* gives its annual consumption of all fossil energy sources, fuel wood, direct uses of mechanical water power, and hydroelectric power starting in 1800, while *Figure 2.6* (Nakicenovic, 1984 and 1986) shows the substitution among these energy sources. Mechanical power (mostly water and some windmills) and hydropower cannot be seen in the figure due to their low contribution to the total energy supply. They

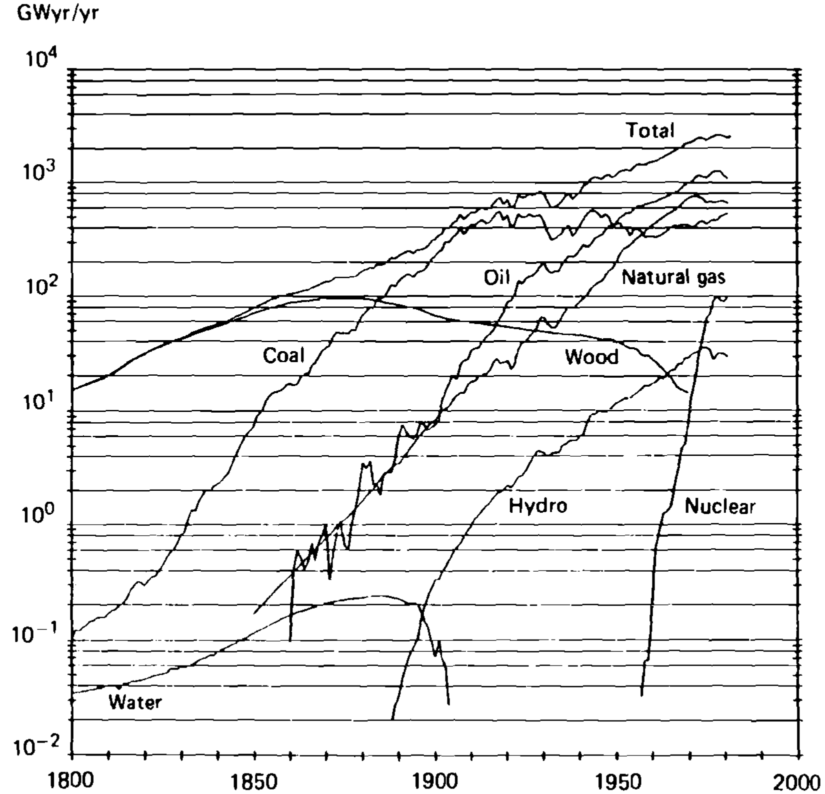

Figure 2.5. US primary energy consumption.

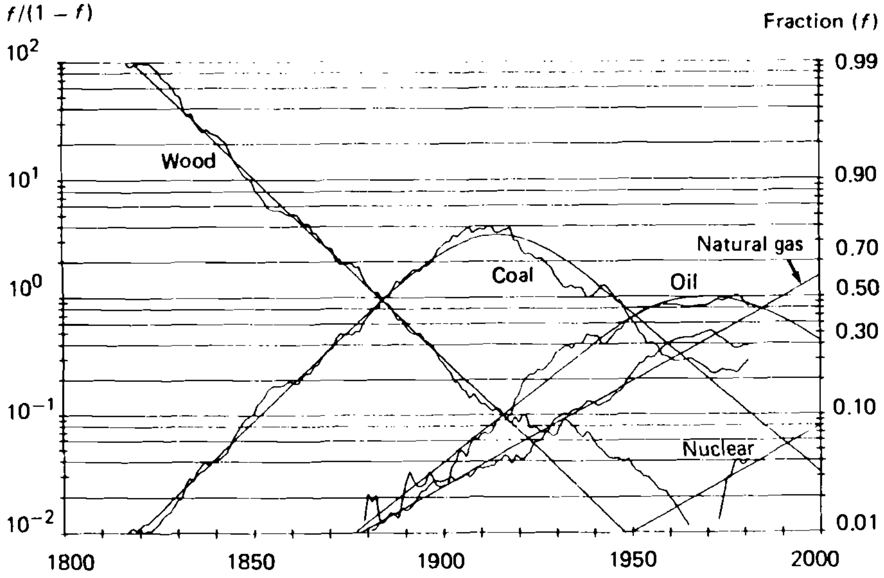

Figure 2.6. US primary energy substitution.

barely exceed the 1% level for very short periods and otherwise fall under that critical level. Thus, before the 1820s, fuel wood provided virtually all the energy needs of the USA. Coal entered the competition process in 1817 at the 1% level, and up to the 1880s the market was essentially based on these two technologies – whatever gains coal made were translated into losses for fuel wood. Wood, however, remained an important source of heat and power for industrial purposes well into the second half of the nineteenth century.

In the USA, the steam age began in the fuel wood-based economy. The first steamboats and locomotives were fired with wood, which remained the principal fuel used by railroads until about 1870 (Schurr and Netschert, 1960). The iron industry was another large wood consumer. Around 1850, more than half of all the iron produced was still smelted with charcoal. Nevertheless, during this early period of industrialization, the USA was still basically a rural society, so that the total amount of fuel wood consumed in manufacturing and transportation was small compared to the huge quantities used in households. In 1880, the domestic use of fuel wood still accounted for more than 96% of fuel wood consumed (Schurr and Netschert, 1960). At the same time, however, coal was already supplying almost half of all energy needs, most of it being used by emerging industries. In 1880, coal supplied almost 90% of the fuel used for smelting iron. The end of the last century therefore marks the beginning of the industrial development period in the USA.

The first use of crude oil and natural gas in the USA dates back to the beginning of the nineteenth century, and during the 1880s it reached the 1% market share. From then on, the use of crude oil expanded somewhat faster as time progressed, and in 1950 crude oil consumption surpassed that of coal. The use of natural gas surpassed that of coal nine years later. It should be noted that, as late as the 1920s, the use of crude oil was not much larger than the consumption of fuel wood.

It is remarkable that the structure of energy consumption changed most during the period of oil dominance. The 1950s – when oil became the dominant source of energy – represent the beginning of more intense competition between various energy sources both in the USA and in the world. For over 150 years whichever energy source dominated the contemporary energy supply also contributed more than half to all primary energy consumption – from 1800 to 1880 this was fuel wood, and from 1880 to 1950 it was coal. During the 1970s, crude oil was close to achieving a 50% share, but before actually surpassing this mark its dominance began to decline. Thus, during the last three decades, three important sources of energy have shared the market, without a single source having overall dominance, which differs from the pattern observed during earlier periods.

Figure 2.6 indicates that, after the 1980s, natural gas would become the dominant energy source, although crude oil would still maintain a roughly 30% market share by the end of the century. Similarly at the global level, future potential competitors of natural gas, such as nuclear or solar energy, have not yet captured sufficient market shares to allow an estimation of their future penetration rates. The starting point for market penetration of nuclear energy can be dated back to the 1960s, when nuclear power acquired slightly less than a 1% share of primary energy. Making allowance for further cancellations of planned power plants and possible decommissioning of those in operation and construction, we have assumed that nuclear energy could at most double its current 4% market share to about 8% by the year 2000. This leaves natural gas with the lion's share of primary energy, advancing its position to the dominant energy source after this century closes.

2.5. Dynamics of Oil and Natural Gas

The earliest historical records of natural gas drilling and use are reported in ancient China, where natural gas was discovered incidentally during the drilling of brine wells (cf. Brantly, 1971; Gaz de France, 1970 and 1971; and Peebles, 1980). These ancient wells were completed with percussion drills and bamboo casings. Some of the oldest wells were reported by Confucius in 600 B.C. to have reached 500 meters and to have produced natural gas that was transported in bamboo pipes for use in evaporating brine to recover salt. By the nineteenth century, this drilling technology improved in performance by almost an order of magnitude. Visitors to China have described drilling depths of up to 4,000 meters, which is comparable to the depths of many commercial wells today. In fact, some of the first natural gas discoveries in the West were also the result of drilling brine wells. Just as in China, the first significant use of natural gas was to dry salt, one of the largest energy consumers among the modest production processes in the pre-industrial age.

2.5.1. Drilling performance and average depth

Modern drilling technology for oil and gas developed originally in the methods used for brine and water wells. The first producing oil well was completed in 1745, in the French Pechelbronn oil field. Drilling technology gradually improved, and by the 1850s, depths of about 600 meters were achieved in France with dry rotary rigs. In the USA, similar depths were reached during the same period with cable tool rigs.

The significant advances in drilling technology since the 1850s were primarily a result of intensive oil drilling, especially in the USA. Probably the most important single innovation in drilling methods was the hydraulic rotary rig, which was introduced around the turn of the century. The dramatic improvement in the performance of drilling technologies during the last 100 years is illustrated in *Figure 2.7*, which shows the drilling depth records for the three most important technologies: dry rotary and

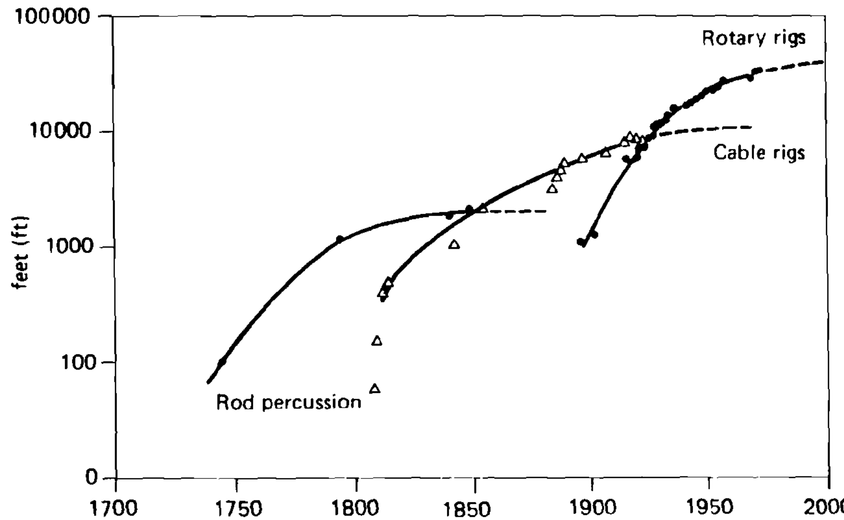

Figure 2.7. World drilling depth records

rod percussion, cable tool, and hydraulic rotary rigs. The data for this figure are taken from Brantly (1971) and *Oil and Gas Journal* (1977). Two small-diameter core test drillings in Germany were excluded from the data, one reaching 2,000 meters in 1893 and the other 2,240 meters in 1909, because they were not exploratory wells for commercial production of hydrocarbons. It can be seen from *Figure 2.7* that both of the new drilling technologies were inferior to the older competitor in terms of record depth at the time of their introduction. In time, however, the new technology overtook the older one to establish and improve the depth records.

In terms of petroleum geology, this trend favors natural gas since the probability of finding methane increases with depth, and that of discovering oil decreases. Between depths of 1,000 meters to a few thousand meters, the hydrocarbon deposits are mostly in the form of crude oil. Thereafter, the likelihood of oil deposits decreases, and below 4,000 meters virtually all hydrocarbon deposits are methane or methane with carbon dioxide (see Donat, 1984). Geological evidence and the chemical characteristics of hydrocarbon compounds indicate a very low probability for the occurrence of more complex molecules (crude oil) below these depths and an increasing probability of finding methane at greater depths due to high pressure and temperature (see Gold, 1985).

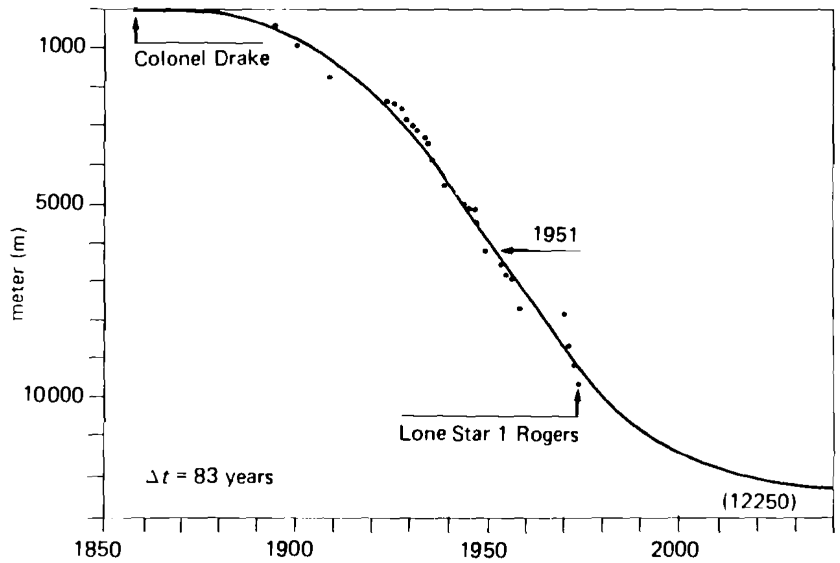

Figure 2.8. US maximum depth of exploratory drilling. Data sources: API (1971) and IPE (1978 and 1983).

Technological progress in drilling, expressed in terms of maximum depth, indicates that new record wells, if successful, can be expected to find methane, not crude oil. In fact, virtually all recent record wells or deep wells were drilled for natural gas exploration. Thus, it is equally interesting to look at the evolution of record depths drilled during the last 100 years for all technologies from *Figure 2.7* taken together. *Figure 2.8* shows the exploratory drilling depth records in the USA, culminating with the Lone Star 1 Rogers, completed during the 1970s, as the deepest exploratory well drilled. This record will most likely be exceeded in the future. *Figure 2.8* shows that the logistic trend in deep drilling would reach an asymptotic depth record exceeding 12,000 meters.

Thus, while the decoupling of oil and natural gas technologies is not reflected in drilling technologies, since these are still basically identical whether the well is drilled for oil or gas, most of the record wells reaching depths below a few thousand meters were primarily natural gas wells in the Anadarko Basin. This tendency toward deeper exploratory wells should favor additional gas discoveries since the probability of finding oil below 10 km is virtually zero. In fact, most of the recent technical improvements in rigs and drillbits are designed for deep wells, both scientific research wells (such as the Soviet effort on the Kola Peninsula) and natural gas prospecting efforts. At the same time, there is some indication that, at greater depths, potentially large unconventional and abiogenic methane deposits may be found (see Gold, 1985). The long-term evolution of drilling technologies to deeper horizons may indeed lead to the overwhelming dominance of natural gas in successful wells, especially as the more readily available oil deposits become exhausted.

In this context, it is interesting to note that these saturation trends in drilling depth records cannot be observed for offshore drillings. *Figure 2.9* shows the worldwide offshore depth records for commercial exploratory drilling (API, 1986; IPE, 1983; and *Ocean Oil Weekly Report*, 1986). The progress achieved since the first so-called oil shock of 1973 is especially noteworthy. *Figure 2.9* indicates that a considerable potential exists for a further increase in the share of offshore gas production, which currently accounts for about 20% of global gas production. It has, in fact, been estimated that up to 40% of the undiscovered oil and gas reserves may be found offshore (Klemme, 1977).

The evolution of exploratory drilling indicates that a long-term trend toward a higher natural gas-to-oil well ratio can be observed for the USA. Although the conventional exploratory drilling technology reached rather shallow depths during the last century (compared with eight or more kilometers today), nevertheless the effect of gradually decoupling methane from oil technologies can be observed. The USA has been chosen for study primarily because of the availability of almost complete historical time series for drilling activities and because of US technological leadership in this field since the beginning of the industry.

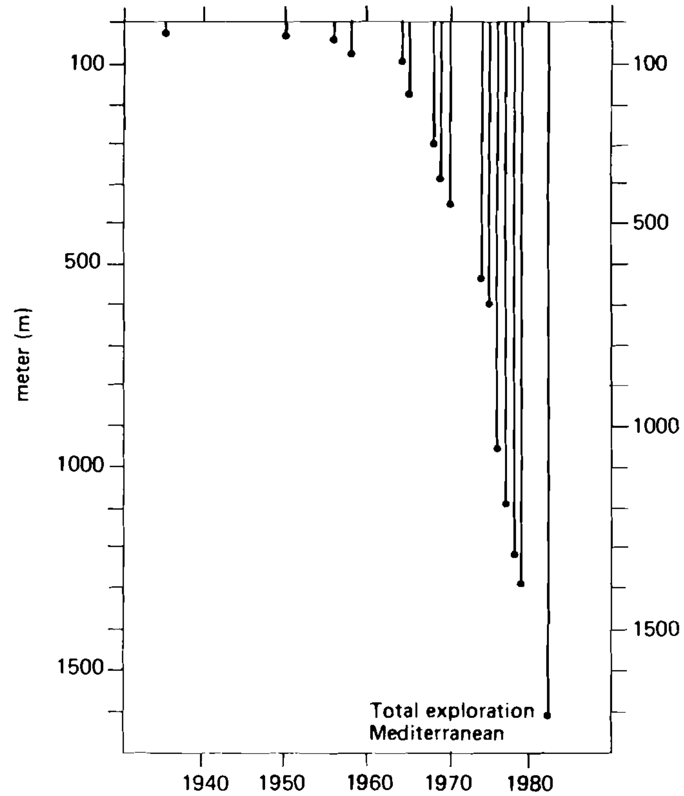

Figure 2.9. World water depth records in exploratory drilling. Data sources: API (1986) and IPE (1983).

Figure 2.10 shows the total number of exploratory wells drilled in the USA since 1900, subdivided into oil, gas, and dry wells (API, 1971 and 1986). Alternative drilling statistics have been compiled by the USGS and published in the yearly issues of ***Mineral Resources of the USA***. These statistics indicate a much greater number of gas wells drilled, especially in the early period. For instance, the cumulative number of gas wells drilled up to 1908 is reported by the USGS as being 21,300, whereas the API statistics give a cumulative total of 3,185 to the same year. Clarification of such differences would require further historical analysis. Service wells are excluded from the drilling statistics used in the examples. Equally, when dealing with these statistics, it is important to note that, during the early period (i.e., before the 1920s), many natural gas finds, discovered in the course of oil exploration, may have been classified as dry holes, due to the lack of a commercial value of a great part of the deposits discovered.

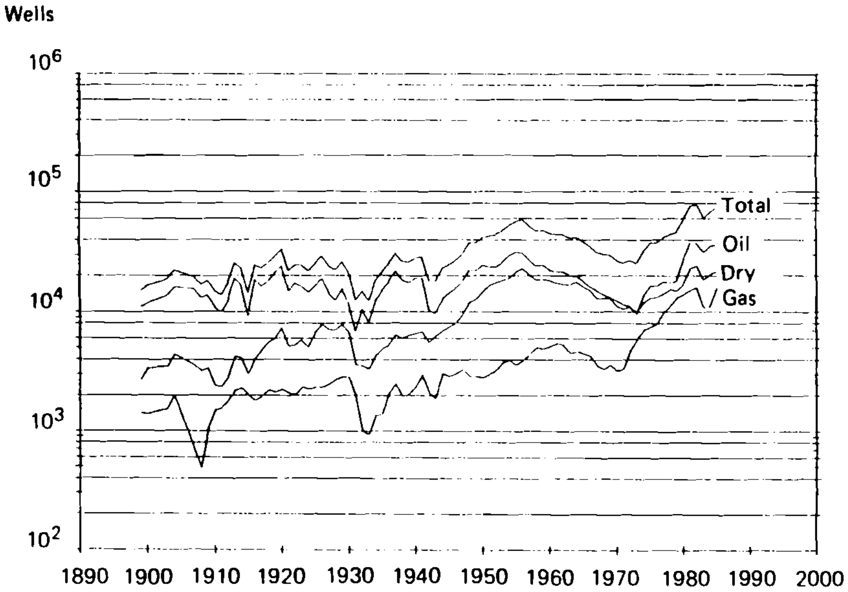

Figure 2.10. USA: number of wells drilled.

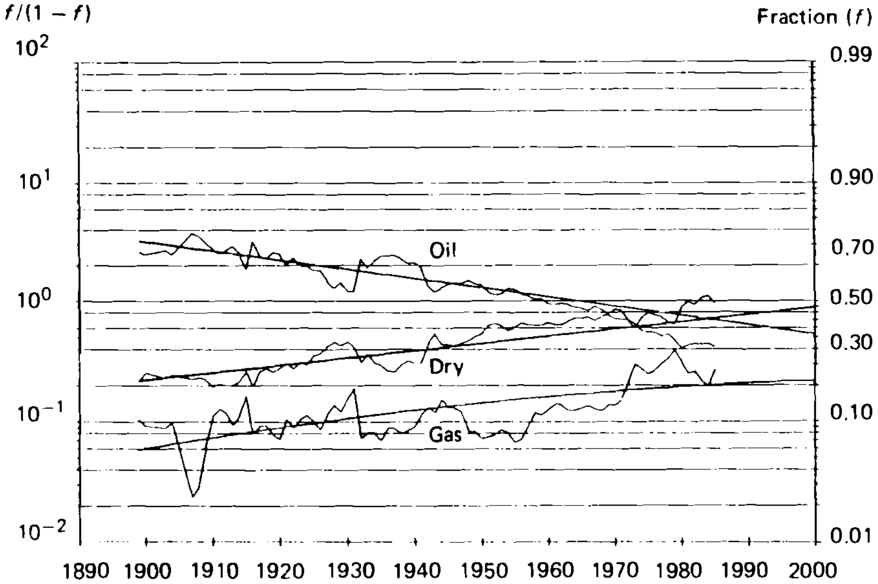

Figure 2.11. US share of oil, gas, and dry wells in total drillings.

Despite these possible shortcoming of the official API drilling statistics, however, *Figure 2.10* indicates a large increase in the total number of wells drilled since 1900, and also large fluctuations, with particularly strong dips in drilling activity during the 1930s and 1960s. *Figure 2.11* shows that these fluctuations disappear, and strong secular trends emerge, when the total drilling effort is viewed as a "market niche" for oil, gas, and dry wells. Defined in this way, the shares of gas and dry wells are increasing and the share of oil wells is declining. Thus, the decoupling of oil and gas technology is manifested implicitly in drilling statistics. Although oil wells still represent the majority of wells drilled, the number of gas wells is on the increase. Unfortunately, this development has been paralleled by an increase of dry wells; but since the late 1960s, there are signs of a reversal, perhaps indicating the use of improved exploration methods such as geophysical surveying.

Figure 2.12 shows the shares of oil and gas discoveries in productive wells by excluding dry wells. This transformation of the substitution process emphasizes the different historical trends in successful oil and gas wells. The "market penetration" of gas wells does not exceed the 10% market share until the 1950s, and thereafter shows a steady increase. It is curious, if perhaps only coincidental, that the beginning of this period of more significant increases in the shares of successful gas wells starts during the 1950s, the period when the largest improvements in drilling depths

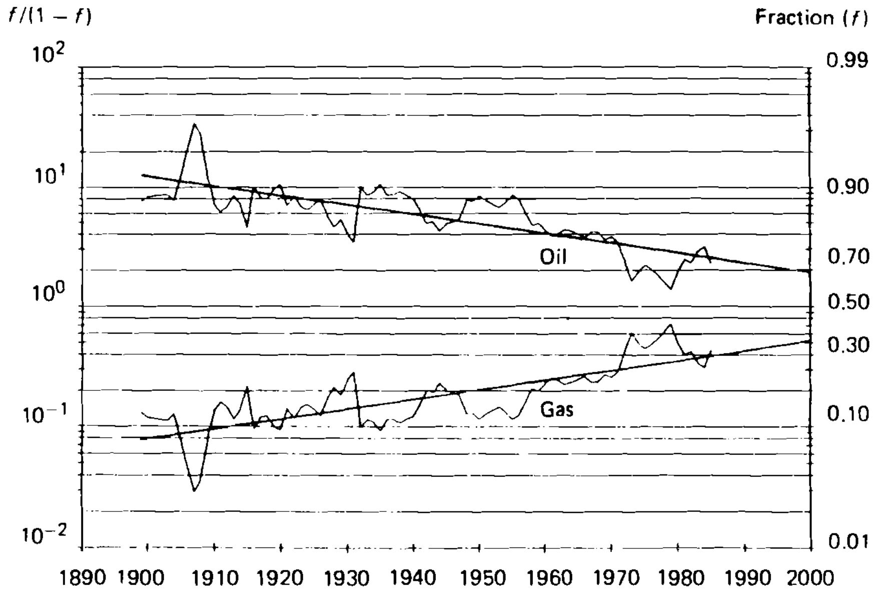

Figure 2.12. US share of successful oil and gas wells.

were achieved, as was illustrated in *Figure 2.8* (the inflection point occurred in 1951). Based on an extrapolation of the long-term historic trend, one might expect for the year 2000 that slightly over 30% of all successful wells drilled in the USA will yield gas and less than 70% will yield oil, compared to a 10:90% relationship between gas-to-oil finds characteristic of the earlier period.

There is no doubt that the historical trends indicate success ratio improvements in methane exploration and decreases in oil exploration. These long-term trends are strengthened by the fact that the best performance in exploration wells indicates a further advance of drilling technology to reach depths where only methane can be expected, due to the high temperature and pressure conditions. Thus, the best performance in drilling technology suggests an increasing decoupling of natural gas finds from those of oil. An important question is whether similar developments can be observed for the performance of the exploratory drilling in terms of the natural gas reserve additions per well or per footage of actual successful gas wells completed.

Figure 2.13 shows a very pronounced change in the secular trend of natural gas reserve additions after the discovery of the Prudhoe Bay field

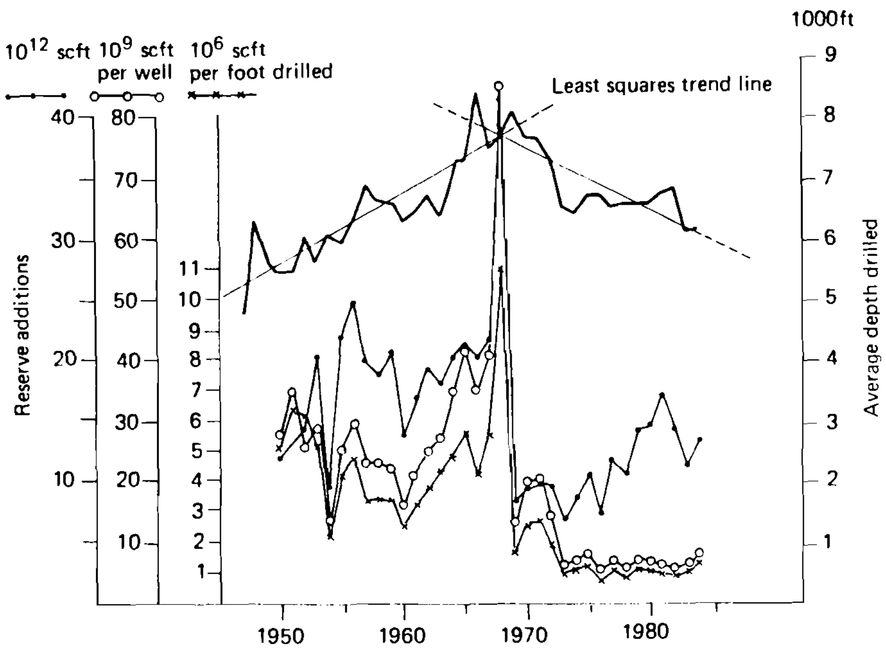

Figure 2.13. US natural gas reserve additions and drilling depth.

in 1969 (the actual reserve additions are backdated to year of discovery). For the figure, the net natural gas reserve additions (from discoveries in new fields and pools as well as the extensions and revisions from known reservoirs) are compared to the number of successful exploratory gas wells (i.e., excluding development wells). Sources of data are AGA (1972, 1975–1979, and 1984) and API (1986). Ever since 1969, the yield per well or per footage drilled has been considerably lower than during the 1950s and 1960s, as shown in the figure. Thus, although the total reserve additions started increasing again after 1969, the additions per well or footage drilled have been rather constant during the last decade despite increases in the share of successful gas wells in the total number of wells drilled (from *Figure 2.5*).

It is perhaps not coincidental that this decrease or lack of improvement in exploratory natural gas drilling in the USA is accompanied by a secular trend change in the average depth drilled (see the least squares trend lines in *Figure 3.5*). The average depth drilled per well increased from about 5,000 feet in the early 1950s to about 8,000 feet by 1970. Thereafter, it has been decreasing, and currently it is slightly deeper than 6,000 feet. Considering the fact that the number of operating rigs has also decreased from about 8,000 to less than 2,000, it is not very likely that another trend reversal will occur in the near future.

Although it is generally dangerous to attempt an explanation based on rather sparse information, it is possible that the decrease in the yield of exploratory natural gas drilling may simply be the result of the fact that wells are tending to become shallower or that the statistics on discovery rates are inaccurate, since it is often a problem of definition as to whether a certain well is successful and what its potential yield might be. Thus, we can speculate on two possible explanations for this change in the yield of exploratory drilling. The first one would simply imply that the wells were not deep enough (as reflected in the decrease of the average drilling depth of some 1,500 feet in the period from 1970 to 1985) to discover large deposits. Consequently, although the share of successful gas wells was increasing with respect to oil wells, only comparatively small fields were discovered, resulting in lower yield rates per well or foot drilled. An alternative (perhaps more plausible) explanation would be that the drilling statistics are distorted by specific conditions of the tax system, resulting in an important number of "tax write-off" drillings not aimed at discovery and subsequent production. If this were the case, such wells would distort the data by introducing a bias into the drilling statistics, e.g., wells would be reported as successful even if only insignificant amounts of gas were discovered, thus decreasing the resulting yield ratios. Nevertheless, *Figure 2.13* suggests that the drilling depth is an important variable to be considered for the potential success and yield ratios of a gas well. This is consistent with the indications that the success ratios (in terms of resource *discovery*) of deep wells (below 16,000 feet) have been extremely high in the USA. In terms of resource *recovery*, however, not all of these wells are reported as successful due to technical or economic infeasibility of production (Whitmore, 1986).

This brief account of technological improvements in drilling technology and historical records of US natural gas finding rates indicate that there is an increasing decoupling of oil and methane technologies, although the traditional drilling technologies were practically identical, whether the well was explored for oil or gas. This decoupling is suggested by ever deeper exploratory wells that exceeded the depths at which one could reasonably expect to find oil during the 1950s. Thus, the deepest wells during the last three decades were all drilled for methane exploration. At the same time, the ratio of successful natural gas wells has increased since 1900, while the ratio of successful oil wells has decreased. Therefore, we find strong evidence that future improvements in drilling technologies will favor natural gas discoveries and improve yields, despite the fact that oil is still the dominant form of energy. However, the future improvements in drilling technologies will also have to result in large cost reductions in order for deep gas deposits to become competitive with other fossil resources.

2.5.2. Oil and natural gas production

Already the generic name "oil and gas" indicates that, during most of its century-old history, natural gas or methane was known as a by-product not only of oil exploration, but also of oil production. During the early days, natural gas was essential, but often a nuisance to the oil producer. Methane pressure in an oil and gas deposit served to pump the oil to the surface, but it was a nuisance because the gas that actually reached the surface had to be flared in order to avoid the danger of explosion. Thus, natural gas was in fact extracted together with oil, but was usually wasted. At the same time, city gas (mostly methane) was being produced from coal and oil to supply premium fuel, especially for lighting and domestic uses. It is not surprising, then, that some associated gas was soon used for consumption.

According to Schurr *et al.* (1960), the earliest recorded commercial use of natural gas in the New World dates back to 1821 (at the time when coal was supplying just 1% of primary energy, and fuel wood and draft animals the rest), when it was used as lighting fuel in Fredonia, New York. Natural gas continued to be used sporadically throughout the nineteenth century. The first pipeline was constructed from Murrysville to Pittsburgh (Pennsylvania) in 1883, after the discovery of a large well in 1878. Despite such pioneering projects by the emerging oil and gas industry, methane was generally considered to be a waste product. By 1878, both crude oil and natural gas passed the 1% share in primary energy consumption, but most of the natural gas consumed in the following decades was used in the vicinity of the oil fields.

Although statistics about natural gas disposal are available only since 1935, they indicate that, at that time, only 75% of the gross natural gas production was marketed and around 25% vented or flared. Natural gas waste

was probably considerably higher, since not all venting operations in the course of oil drilling may have been recorded. Natural gas waste decreased, particularly in the period after 1940, through increasing uses of natural gas for repressuring. Still, it is interesting to note that it took until 1974 before natural gas wastes were virtually eliminated, being reduced to account for less than 1% of total gross production, as indicated in *Figure 2.14* (data from Schurr *et al.*, 1960, and AGA, 1972, 1975, 1979, and 1984).

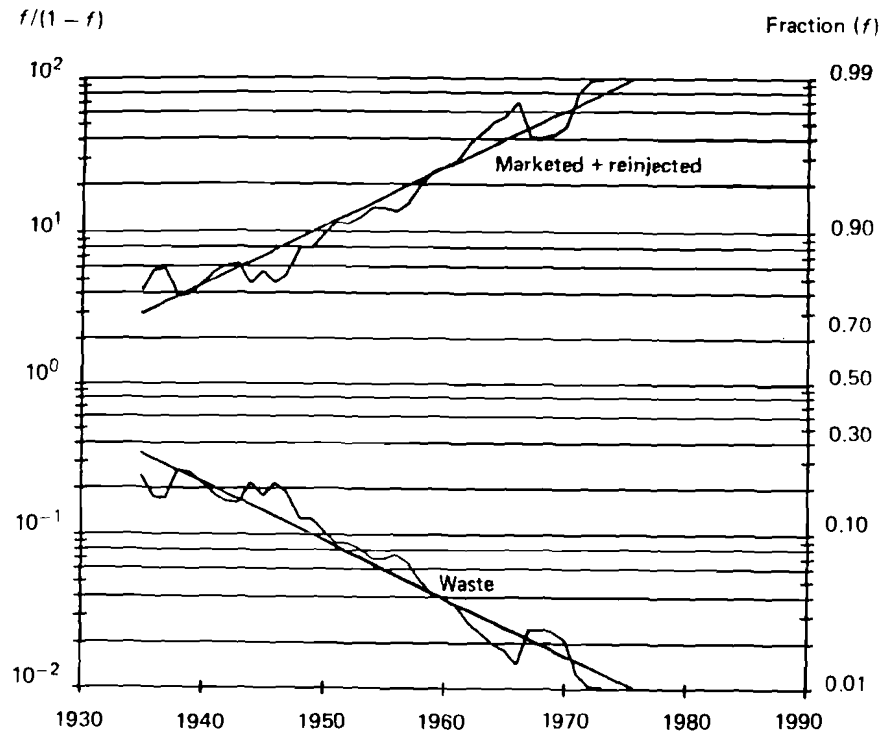

Figure 2.14. US natural gas deposition.

Natural gas production since the turn of the century has grown rapidly, but because, until the last decades, most methane discoveries were related to the search for oil, natural gas extraction was mainly associated with oil production. Accurate statistics of natural gas production from oil and gas wells (associated and nonassociated gas, respectively) are not available for the period before 1935. Hefner (1985) has suggested decoupling associated from nonassociated natural gas production in order to assess the difference, if any, between methane production from oil and gas technologies. *Figure 2.15* shows the steady increase in natural gas production from

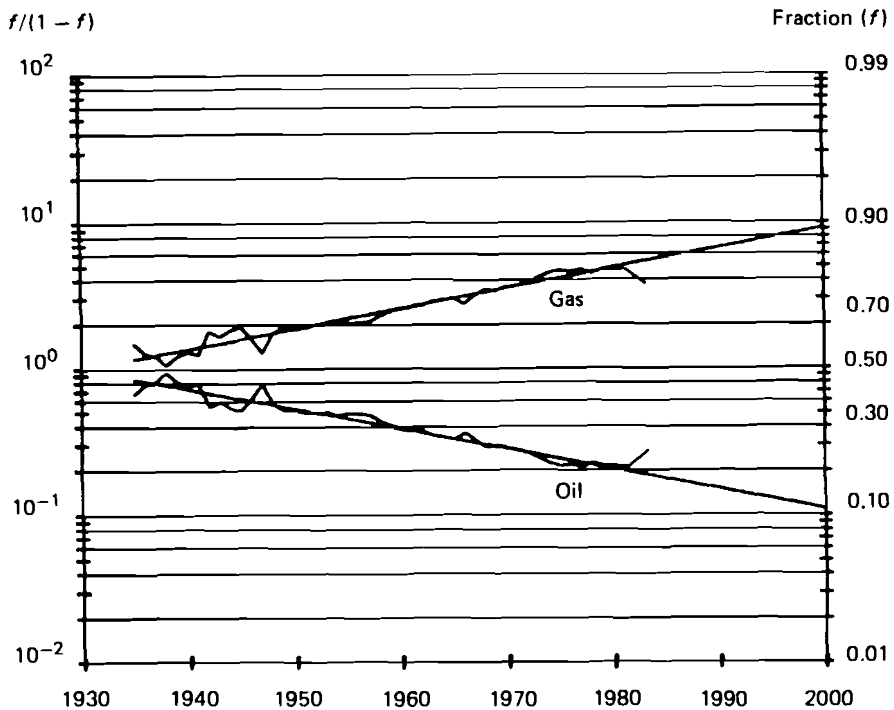

Figure 2.15. US natural gas production from oil and gas wells.

from oil wells (oil technology), but it also shows that by the end of the century 90% of production should be from nonassociated deposits. The decreasing shares of associated gas in total production illustrate the fact that the natural gas industry is in the process of decoupling itself from oil. Thus, the closely related extraction, transport, conversion, and end-use technologies for oil and methane may be slowly diverging toward increasingly independent paths.

This is encouraging, since it indicates a possible next step in the analysis of the evolution of methane technologies. The division of natural gas into oil and gas technologies indicates that it is conceivable that the oil and natural gas industries may also decouple downstream, going perhaps all the way to the final energy consumer. To investigate this possibility, we will next consider the evolution of different energy transport technologies and especially the development of liquid and gaseous energy transport.

2.5.3. Oil and gas transport

During the last few decades, energy became truly a globally traded commodity. Especially crude oil and its products, but to a lesser extent also LNG (liquefied natural gas) and some high-grade coals, are transported around the world. At these global distances, tankers and other vessels are, at least for the time being, the most efficient mode of energy transport. Over continental distances, however, there is a vigorous competition between many alternative transport modes, some of them dedicated to transport of a particular energy form, such as electricity. Crude oil, oil products, and natural gas especially are transported by a number of different transport modes including barges, vessels, trucks, trains, and pipelines.

In contrast to long-distance oil and gas transport to the consumer, wood was primarily consumed locally, close to the source. Some fuel wood was transported over longer distances, mostly by river flotation, and distributed by waterways or roads. Coal, on the other hand, represents a more concentrated form of energy than fuel wood, and coal mines are a more concentrated source than forests (since coal has a higher heat content per unit weight than wood) so that coal was generally transported over longer distances than fuel wood. An extreme case is the modest overseas coal transport (for instance, the coal exports from England to the continent); but more usually coal was transported nationwide by barges, trains, or trucks (earlier by horse wagons). Thus, the shift from a wood- to coal-based economy was accompanied by the expansion of energy transport over longer distances and by an increasing number of transport modes.

The widespread use of crude oil brought another transport mode in addition to tankers, trains, and trucks – oil pipelines. Pipelines are becoming an important freight transport mode with market shares in total ton-kilometers per year comparable to those of train and truck transport. They are also comparable to railways in terms of the total length of the infrastructure or grid: today the total length of main track in the USA is about 200,000 miles, slightly shorter than crude oil pipelines, which total about 230,000 miles. It is interesting to note that in terms of ton-kilometers, car loads, and revenue, coal transport represents by far the largest commodity group in rail transport. Thus, although the total length of the rail and oil pipeline grids is equivalent, the big difference between the two infrastructures is that, since the 1920s, the railroad system has been declining while oil pipelines have been expanding (see Nakicenovic, 1986). *Figure 2.16* shows the rapid increase in pipeline length for crude oil and petroleum products in the USA.

The expansion of the oil pipeline grid parallels the increase of the crude oil share in total primary energy consumption. Oil reached a 1% share in energy during the 1880s, and at the same time the rapid increase in oil pipeline mileage started and followed exponential trends until the 1930s (the inflection point occurred in 1937). As if by coincidence, oil's largest competitor, coal, reached its maximum share in primary energy during the same decade. Thus, by 1937, about half of the current length of the oil

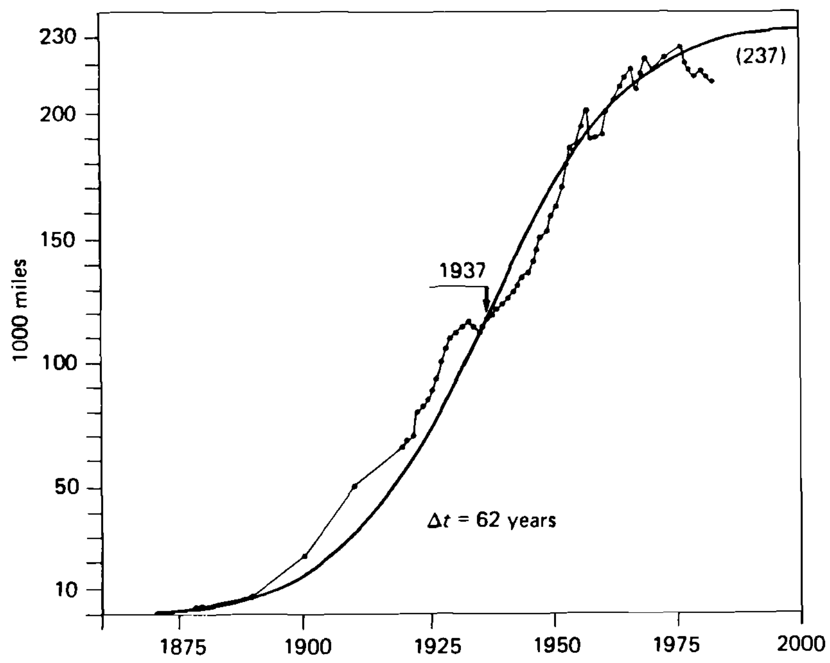

Figure 2.16. US crude and product oil pipeline length.

pipeline network was already in place, and the growth rates declined slowly. During the 1980s, the length should reach the asymptotic level at about the same time as crude oil shares in total primary energy reach saturation. The time constant (Δt) of the expansion of oil pipelines is 62 years or halfway between the time constants for the expansion of rail tracks and surfaced roads of about 50 and 74 years, respectively (see Nakicenovic, 1986).

Although oil is still the most important energy source, in terms of primary energy consumption it is slowly being replaced by natural gas. *Figure 2.15* has shown that the amount of associated natural gas is decreasing in total natural gas production and, therefore, that higher natural gas transport and end-use are based more on gas and less on oil technologies. This process is also reflected in the increase of natural gas transport and distribution pipelines when compared with oil pipelines, shown in *Figure 2.16*. As mentioned above, the first natural gas pipeline in the USA dates back to the 1880s. The rapid expansion of the natural gas pipeline network, however, started during the 1890s, or about 20 years after the growth of oil pipelines was initiated. *Figure 2.17* shows that this 20-year shift in time persists through most of the growth cycle of the natural gas transport system and distribution infrastructure.

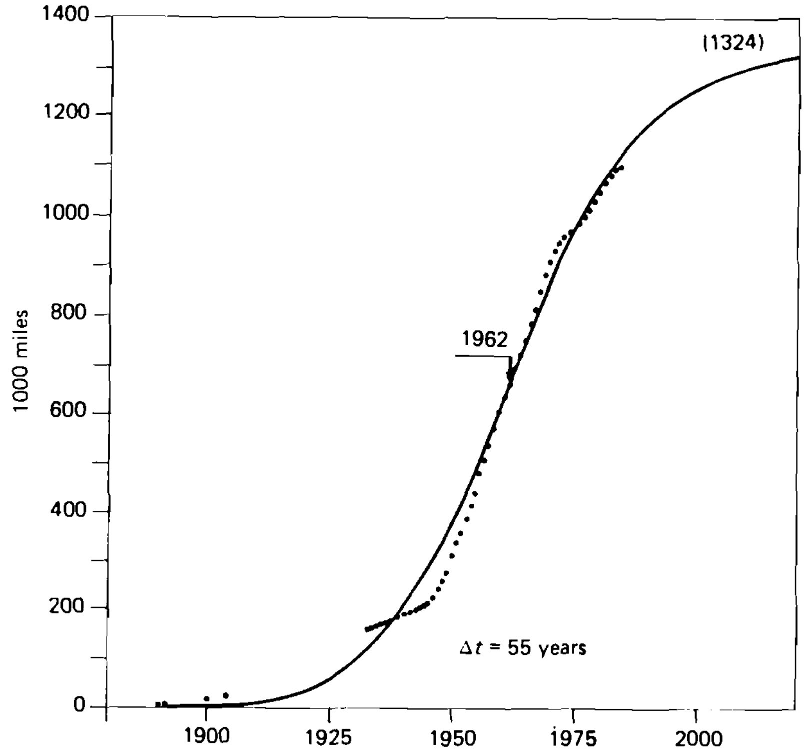

Figure 2.17. US natural gas pipeline length.

The inflection point, with about half the eventual saturation level achieved, occurred in 1962, or 25 years after the inflection in the growth of oil pipelines. Since the time constant is about 55 years, and therefore comparable to that of oil pipelines (62 years), saturation should also occur more than 20 years later, during the 2020s. Again, this is symmetrical with the relationship between the growth phases of oil pipelines and oil penetration in primary energy. The growth pulse started when oil achieved a 1% share of primary energy, inflection occurred during the time when oil became the second largest energy source (bypassing fuel wood), and saturation of pipeline length was synchronous with the saturation of market shares. Exactly the same pattern can be observed during the growth pulse of gas pipelines by comparing *Figures 2.17* and *2.3*. The growth started toward the end of the last century when natural gas achieved a 1% share in primary energy. The inflection point was reached in 1962, when natural gas became the second largest energy source (bypassing coal), and saturation of both natural gas market shares and length of pipeline should be achieved during the 2020s.

A large difference between the growth pulses of oil and gas pipelines is in the length of the respective transport and distribution networks. *Figure 2.16* gives a saturation level estimate for oil pipeline length of about 240,000 miles (or about the current length of railroad tracks; see Nakicenovic, 1986), whereas the asymptotic level for the length of gas pipelines is estimated at more than 1,300,000 miles (more than five times higher). For the time being, natural gas is transported almost exclusively through the pipeline grid. Oil and petroleum products, however, are also shipped by tankers, trains, trucks and, for some military use, even by aircraft. Aside from some smaller quantities of liquefied natural gas and liquid natural gas products, most natural gas reaches the consumer either in a gaseous form or as electricity. The pipeline network for gas transport and distribution is therefore also much longer than that for crude oil and petroleum products. This poses the question of whether we can expect natural gas to continue to be transported almost exclusively by pipelines in the future, especially if its projected use expands as dramatically as illustrated in *Figure 2.3*. For liquid natural gas products especially, it is likely that other transport modes will also be used, conceivably even aircraft. From the technical point of view, there are in principle no obstacles to using this transport mode for energy; the only question is whether it would be economical and competitive to do so.

This point cannot be resolved here, but we mention this alternative for the future because similar solutions have been found in the past to meet the ever increasing need to transport more energy over longer distances. Denser and cleaner energy forms were technological measures needed to improve the performance of the whole energy system. We can therefore expect further improvements in the near future, and these could be fulfilled by a stronger reliance on natural gas.

2.5.4 Energy substitution and end-use

Natural gas exploration, production, and transport indicate significantly different trends from oil technologies, although natural gas has been associated with the oil industry ever since its first commercial use. Nevertheless, most energy accounts bind natural gas to oil because of the large production of associated natural gas from oil wells. Except at the point of production, associated natural gas, or oil-technology gas, is indistinguishable from gas produced from natural gas wells. The fact that this distinction is difficult to make, and is consequently ignored in historical data, is to an extent misleading since we have shown that oil and gas technology have followed distinctly different trends during the last century. In addition, the distinction between associated gas and crude oil in terms of primary energy accounting is consistent with adding city gas produced from oil or coal to these primary energy sources rather than to natural gas. To investigate the hypothesis that natural gas is becoming increasingly decoupled from oil technologies, we have attempted to reconstruct the primary energy

balances by adding associated gas to crude oil and subtracting the same amount from natural gas consumption (but leaving net imports with natural gas balances).

Figure 2.18 shows the resulting refined version of the primary energy substitution dynamics from *Figure 2.6* in the case of the USA. This revised technological substitution process can be characterized by very regular time constants because the historical data are apparently accurate enough to provide the information required for further analytical resolution. This is possible in the case of primary energy consumption because different energy sources can be measured in common (physical, energy) units and because their use is relatively well documented in the USA for the last 190

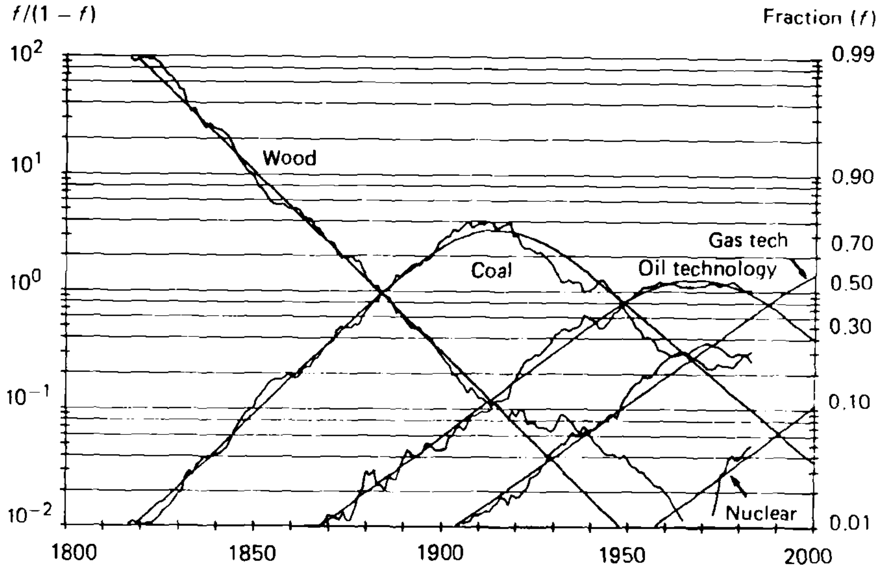

Figure 2.18. US energy substitution and gas technologies.

years. *Figure 2.18* represents such a higher resolution because associated natural gas (oil technology from *Figure 2.15*) is now reallocated to the use of crude oil, leaving only the nonassociated gas from gas wells (including natural gas imports) to "gas technology".

This result shows that, although associated gas has long been available as a by-product of oil, its use does not represent the actual evolution of gas technologies. *Figure 2.18* shows that this refinement of the substitution process improves the regularity to the extent that the time constants now cluster at about 70 years for all energy sources and that the saturation intervals between coal, oil, and gas technologies are all separated by about 50 years. During the saturation periods of the dominant energy sources, new ones are introduced. Gas technologies are introduced during the saturation of coal, and nuclear energy during the saturation of oil. The actual oil shares (with associated gas) have now increased so that the importance of oil during the last decades can be seen as clearly dominating more than half of all energy supplies.

This result is encouraging since it indicates a possible next step in the analysis of the evolution of methane technologies. The division of natural gas into oil and gas technologies suggests that the two industries may also decouple downstream, perhaps all the way to the final energy consumer. In order to investigate this possibility, we consider the evolution of natural gas end-use in different sectors of the economy.

The consumer is faced with the decision of choosing the final energy form of preference and seldom attends to the origin of alternative fuels. Thus, the difference between associated and nonassociated natural gas cannot be made at the level of energy end-use. Instead, we can view the trends in total natural gas use at the level of the whole economy, but cannot distinguish between oil and gas technologies.

Figure 2.19 shows the competition of different branches of the US economy for natural gas. The substitution process is very regular with modest fluctuations of actual data from model estimates [2]. Therefore, the example illustrates a continuous and steady trend toward greater use of natural gas in the residential and commercial sectors. At the same time, the share of natural gas used for industrial purposes is decreasing. This result clearly shows that natural gas does indeed have the characteristics of a premium fuel. Industry usually has more technological opportunities to switch between fuels and to implement environmental control when dirtier fuels are utilized. Residential and commercial sectors, on the other hand, usually represent smaller-scale users in relatively densely populated areas. Thus, it is natural to expect that the cleanest available fuel should be utilized. Next to electricity, natural gas is the cleanest final energy form.

With ever more stringent environmental controls and an increasing need for convenience in energy end-use, this trend toward larger shares of natural gas used in residential and commercial sectors should be expected to continue, as *Figure 2.19* suggests. Considering that many studies indicate that the current economic structural changes in the industrialized countries favor expansion of the service sector compared with manufacturing, *Figure 2.19* implies that this restructuring process would also favor an increased use of natural gas, since increasing shares of natural gas are consumed in the residential and commercial sectors. Thus, growing sectors can be expected to become the largest natural gas consumers, while industry and especially some transport modes may rely more on liquid energy carriers. This does not preclude the possibility that, in addition to electricity, liquid energy forms may be produced from natural gas in the next decades.

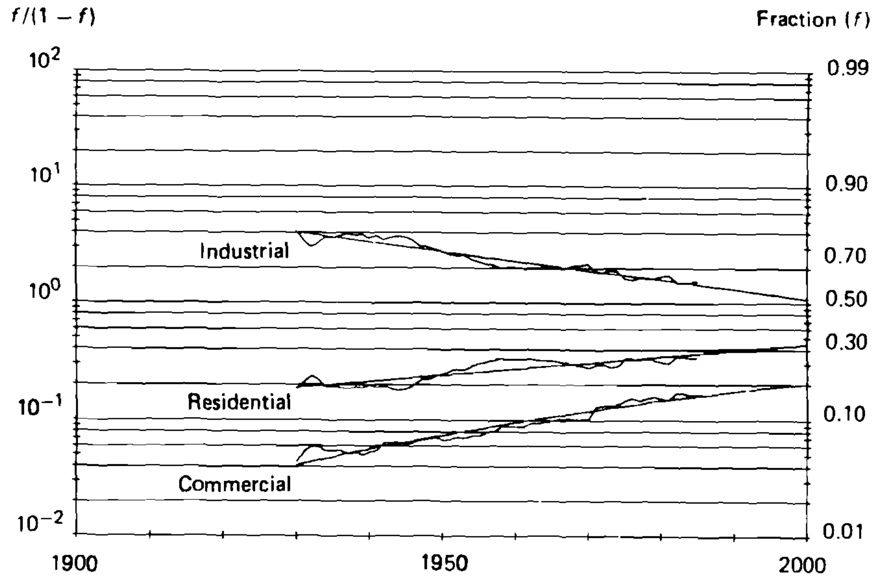

Figure 2.19. US natural gas use by economic sector.

2.5. Conclusions

In a number of examples analyzed in this chapter, we have shown that the growth and senescence of energy technologies can be described as a regular process with logistic secular trends. The dynamics of primary energy substitution in the world and most of the countries and regions analyzed to date (see, e.g., Marchetti and Nakicenovic, 1979, and Nakicenovic, 1984) indicate that natural gas could become the energy source of choice during the coming decades. In this chapter, we have considered this transition from oil to gas as the dominant source of energy at different stages of the energy system from exploration and production to energy consumption and end-use. Throughout the energy system, there are clear indications that natural gas technologies (e.g., exploration and transport) are still in the growth phase, whereas oil technologies are apparently close to saturation. Most of the examples analyzed here are from the USA, primarily because of the US leadership in natural gas use and technologies in the past, and because of data availability.

The refined version of the primary energy substitution process in the USA, based on decoupling oil and gas production technologies as shown in

Figure 2.18, indicates that technological substitution can be characterized by very regular time constants, provided that the historical data are accurate enough to supply the information required for further analytical resolution. In this example, associated natural gas is reallocated to oil technology, and nonassociated gas from gas wells to gas technology. This refinement of the substitution process so improves the regularity that the time constants cluster at about 70 years for all energy sources; and the saturation intervals between coal, oil, and gas technologies are also separated by about 50 years. During the saturation periods of the dominant energy sources, new ones are introduced. Gas technologies are introduced during the saturation of coal, and nuclear energy during the saturation of oil (including associated gas technologies). The penetration rate of gas technologies is comparable to the penetration rate of oil and coal, leading eventually to a similar pattern of market penetration and a resulting market dominance in the next century.

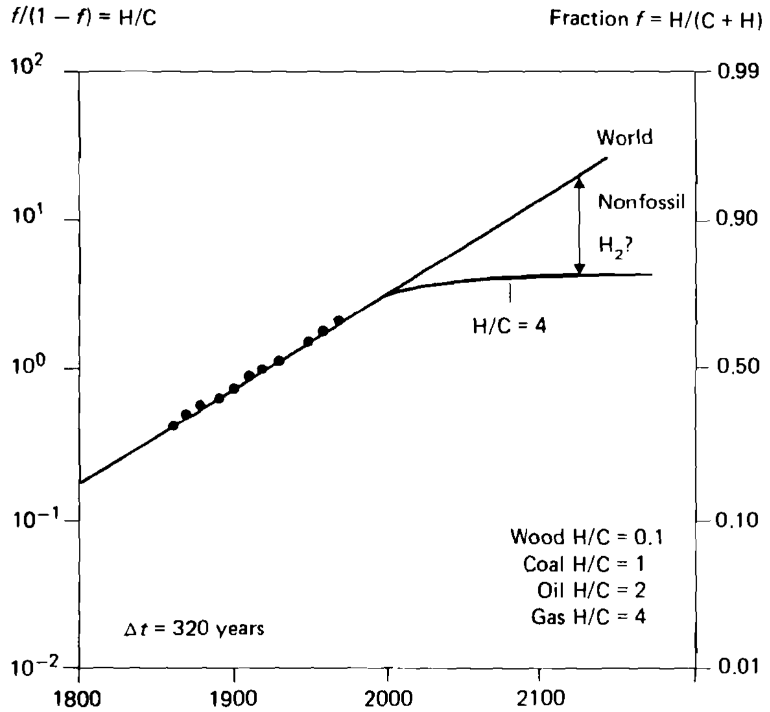

Figure 2.20. World hydrogen-to-carbon ratio of primary energy.

Thus, despite the fact that natural gas use has not increased much during the last few years, in contrast to the growth rates experienced during the earlier decades, our results indicate that the growth potential of natural gas technologies is still very large, especially when compared with oil technologies, which appear to be reaching saturation in the USA. It is very likely that this potential for improving natural gas technology will continue during the coming decades, leading to the development of specific technologies tailored to natural gas that will not be mere derivatives of oil technologies, as they have been in the past. A prerequisite for the widespread use of natural gas in the future is, in our opinion, the decoupling of methane from oil technologies, and this process was initiated long ago when associated gas supplied most of the natural gas consumed. Our results show that the dynamics of energy substitution and methane technologies represent evolutionary, rather than revolutionary, processes that could meet more stringent future requirements through refinements and improvements in current designs and practices during the next two decades. Potentially, methane is cleaner, and it may be distributed abundantly and more evenly throughout the world, than other fossil energy sources.

Thus, methane fulfills most of the obvious future requirements for becoming the major source of energy. A bonus in terms of the very long-term prospects could be that the natural gas economy can pave the way for a very clean hydrogen future. *Figure 2.20* (Marchetti, 1982) illustrates the possibility of such an evolutionary transition in the world from original reliance on fuels with relatively low to fuels with higher hydrogen content; hydrogen-to-carbon ratios were calculated on the basis of actual energy consumption, as specified in *Figure 2.20*, for wood, coal, oil, and natural gas.

This transition is presented as a "substitution" process of hydrogen for carbon in the total primary energy consumption during the last century. *Figure 2.20* shows that, after this century, the hydrogen-to-carbon ratio may exceed the level that can be achieved by pure methane economy, implying that some additional hydrogen could be needed to supplement the increasing reliance on methane. In the meantime, the natural gas share in total primary energy should continue to grow at the expense of dirtier energy sources – coal and oil.

Notes

[1] One general finding of a large number of studies is that substitution of an old technology by a new one, expressed in fractional terms, follows characteristic S-shaped curves. Fisher and Pry (1971) formulated a simple but powerful model of technological substitution by postulating that the replacement of an old by a new technology proceeds along the logistic growth curve:

$$\frac{f}{1-f} = \exp(\alpha t + \beta)$$

where t is the independent variable usually representing some unit of time, α and β are constants, f is the fractional market share of the new competitor, while $1-f$ is that of the old one.

In dealing with more than two competing technologies, we must generalize the Fisher and Pry model, since in such cases logistic substitution cannot be preserved in all phases of the substitution process. Every competitor undergoes three distinct substitution phases: growth, saturation, and decline. This is illustrated by the substitution path of coal, which curves through a maximum from increasing to declining market shares (see *Figure 3.2*). In the model of the substitution process, we assume that only one competitor is in the saturation phase at any given time, that declining technologies fade away steadily at logistic rates, and that new competitors enter the market and grow at logistic rates. As a result, the saturating technology is left with the residual market shares (i.e., the difference between 1 and the sum of fractional market shares of all other competitors – growing or declining) and is forced to follow a nonlogistic path that joins its period of growth to its subsequent period of decline. After the current saturating competitor has reached a logistic rate of decline, the next oldest competitor enters its saturation phase, and the process is repeated until all but the most recent competitors are in decline. A more comprehensive description of the model and the assumptions is given in Nakicenovic (1979).

[2] In fact, this example illustrates the predictive power of the logistic substitution approach in forecasting market shares. This particular example was reported in Marchetti and Nakicenovic (1979), with data up to 1976, so that the period from 1976 to 1985 represents an actual forecast of nine years. Comparison with the original publication shows that the forecast was excellent, within a few percentage points for industrial and residential sectors and precision better than 1% for the commercial sector.

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