THE DYNAMIC EVOLUTION OF METHANE TECHNOLOGIES

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January 1987
WP-87-2

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PREFACE

This paper was prepeared for the Task Force Meeting on "The Methane Age", Sopron, Hungary, 14-16 May 1986, organized by the International Institute for Applied Systems Analysis (IIASA). It is based on research conducted within the scope of the Dynamics of Technology (DOT) project.

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1 INTRODUCTION

The use of natural gas has been increasing in many parts of the world and in most industrialized countries. As a result of these developments, 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 United States, it is second only to oil. Despite these enormous increases in natural gas consumption and related improvements in production, transport, conversion, distribution and end-use technologies, natural gas is still considered as the "step-child" of the oil industry – a by-product of oil production.

This is even more surprising considering the promising prospects of the wide-spread 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 reduced even further by relatively simple measures. In the past, most natural gas discoveries were incidental to oil prospection. Today, there is increasing evidence that methane may be 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 has not increased much during the last few years. The gas bubble still persists because acquiring new markets turned out to be more difficult than 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, tailored to natural gas and not mere derivatives of oil technologies. In other words, a prerequisite for the wide-spread use of natural gas in the future is the increasing de-coupling of methane technologies from oil technologies. As a consequence, the oil and gas industry would eventually be decomposed into two separate entities. Before embarking on the justification of our contention, we will first describe the evolution of the energy system and the dynamics of natural gas. With this historical perspective, we will then outline the future developments likely to lead to the separation of the oil and gas industry and oil and methane technologies.

2 PRIMARY ENERGY CONSUMPTION

At the beginning of the 19th century, fuel wood, agricultural wastes, and mechanical wind and water power supplied most of the inanimate energy in addition to animal and human muscle power. This, by present standards, poor energy menu, represented an already sophisticated energy 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 by piece-wise 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 wide-spread, 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, on average, less rapid growth rates. 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 parallel to 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.

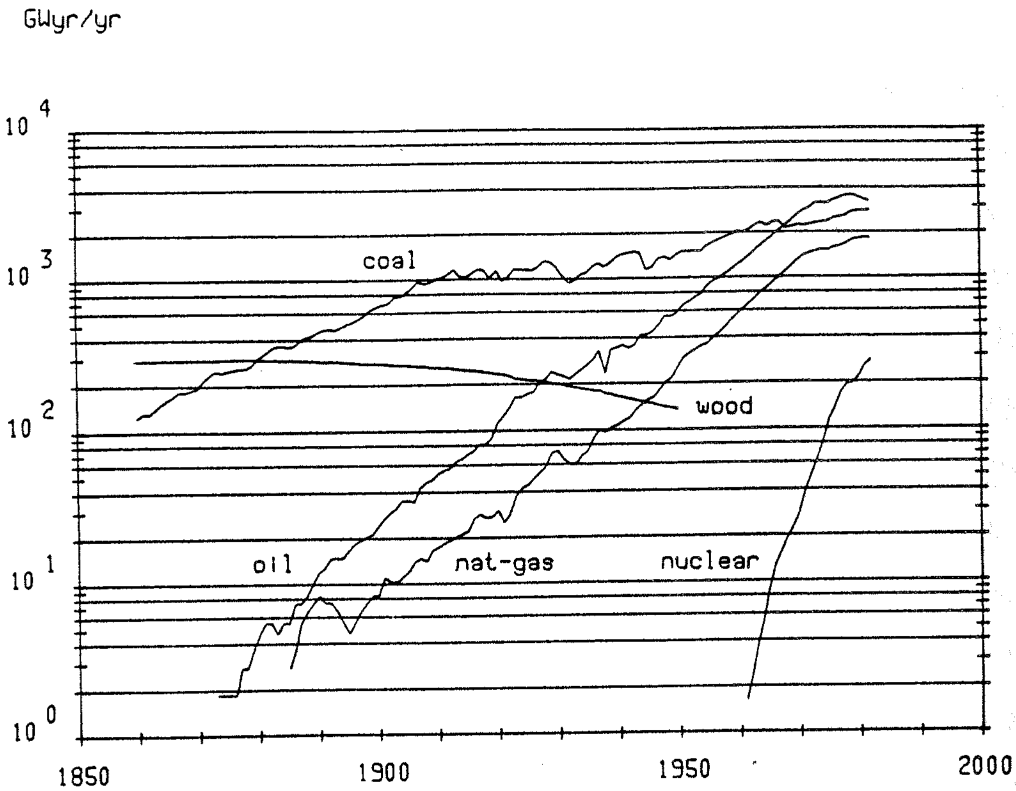


Figure 2.1 Primary Energy Consumption, World.

During recent years, the growth of nuclear energy has declined worldwide to more moderate rates.

Thus, during this period of 130 years, 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) increased exponentially at an average growth rate of 2.3 percent per year. It is evident that the older forms of energy have been replaced by the newer ones. The decline of the older energy sources was compensated by the more rapid growth of the new ones. These dynamic changes are more clearly seen in Figure 2.2 (Nakicenovic, 1984) which shows the fractional market shares of the five most important primary energy sources from Figure 2.1 In terms of fractional market shares, fuel wood had already been replaced by coal during the last half of the 19th century. In 1860, fuel wood

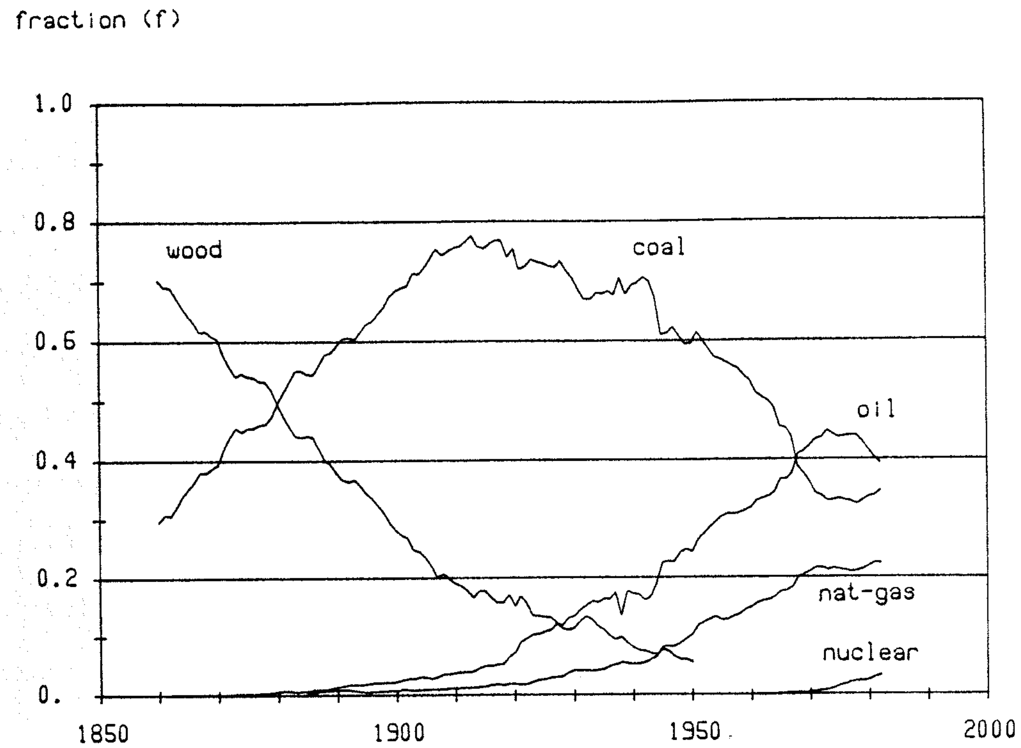


Figure 2.2 Fractional Shares of Major Primary Energy Sources, World.

supplied about 70 percent of consumed energy, but by the 1900s, its share had dwindled to little more than 20 percent. Due 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 percent in 1860, to almost 80 percent 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 fifty 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.

2.1 Natural Gas in the Global Context

The evolution of primary energy use, seen 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 some 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

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, *alpha* and *beta* 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 2.3). 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 saturated 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) and is forced to follow a nonlogistic path that joins its period of growth to its subsequent period of decline. After the current saturated 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).

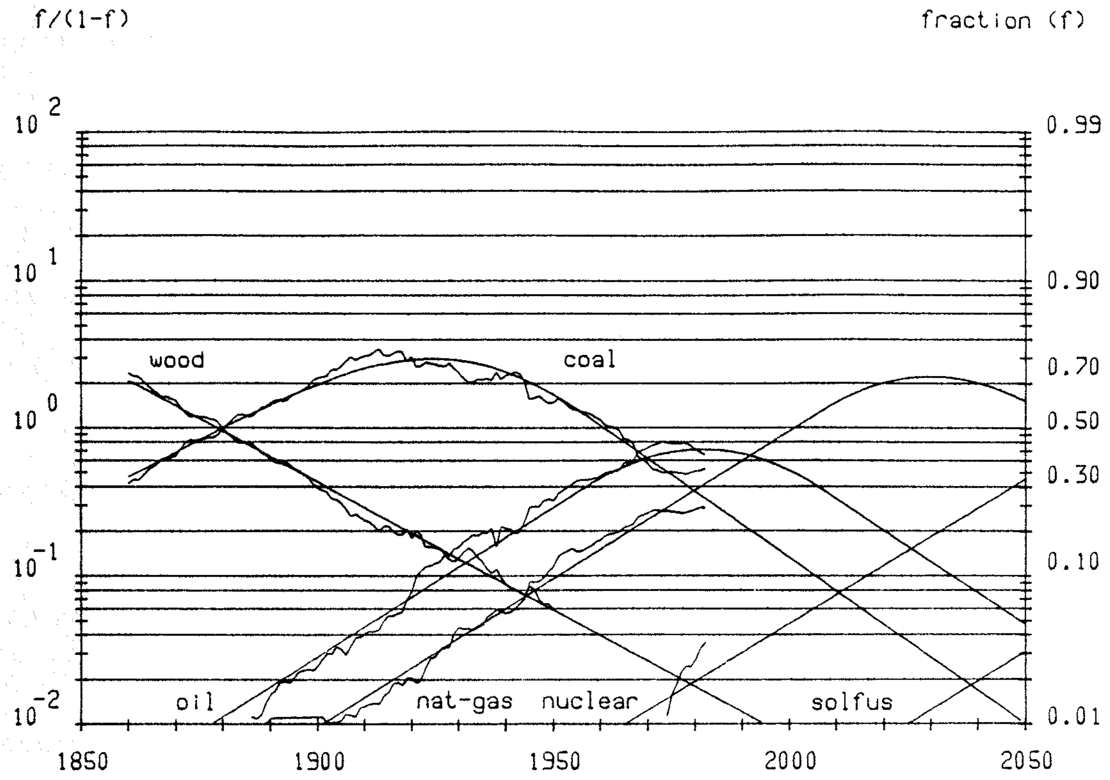
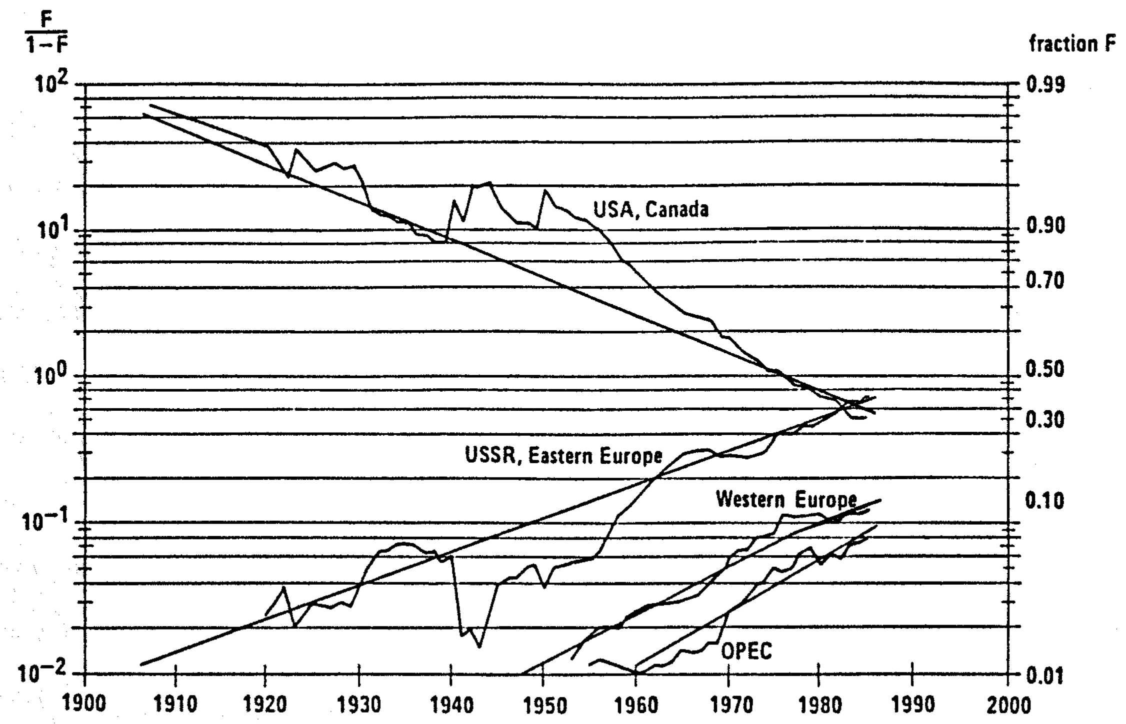


Figure 2.3 Primary Energy Substitution, World (with Projections).

to allow estimation of their penetration rates. We have assumed a more modest nuclear penetration rate to account for possible cancellations and delays in constructing planned power plants. The nuclear scenario, therefore, prescribes a one-percent share in 1965, and a three-percent share 25 years later in 1990 (in 1982, the nuclear share in global primary energy consumption was 3.5 percent). For the next energy source, which we symbolically call "solfus" in order to indicate the potential use of both solar and fusion energy, we have made an equivalent scenario with a one-percent share in the year 2025, and a three-percent in 2050. 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 would 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 have to rely on nuclear or alternative energy sources for another 50 years or so after all. Instead, the possible future that emerges would require less radical changes, but still be a challenging task to develop new technologies and 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 in the long run. In order to gain a better understanding of how such changes may come about, we will first investigate the history of natural gas with a higher degree of resolution. Thereafter, we will return again 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 United States and Canada) was the dominant producer of natural gas until 1983, being superceded by the Soviet Union during the last three years. In fact, the United States has produced most of the natural gas extracted globally since the beginning of the industry and continued to produce still more that half



Note: Residual to total world production not plotted. Market shares do therefore not add to 100 percent.

Figure 2.4 Natural Gas Production, World by Major Regions.

until the middle 1970s. The history of natural gas is, therefore, closely linked to the United States. 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 towards a more widely distributed natural gas production throughout the world should continue, and this is one of the crucial issues associated with the future use of natural gas to which we will return. However, we will next analyze the evolution of natural gas in the United States, because it was the dominant producer and still is the largest consumer of natural gas and because of the data availability.

2.2 Natural Gas in the United States

The evolution of primary energy use in the United States has a longer recorded history than anywhere else in the world. Figure 2.5 gives the 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 of these energy sources. Mechanical power (mostly water and some wind mills) and hydro-power are not observable in the figure due to their low contribution to the total energy supply. They barely exceed the one-percent level for very short periods and otherwise fall under that critical level. Thus, before the 1820s, fuel wood provided for virtually all the energy needs of the United States. Coal entered the competition process in 1817 at the one-percent level, and up to the 1880s it was essentially a two technology market – 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 19th century. In the United States, the steam age began in the economy based on wood use. The first steam-boats 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 United States 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 percent of fuel wood consumed (Schurr and Netschert, 1960). At the same time, however, coal was already supplying almost one-half of all energy needs, most of it being used by

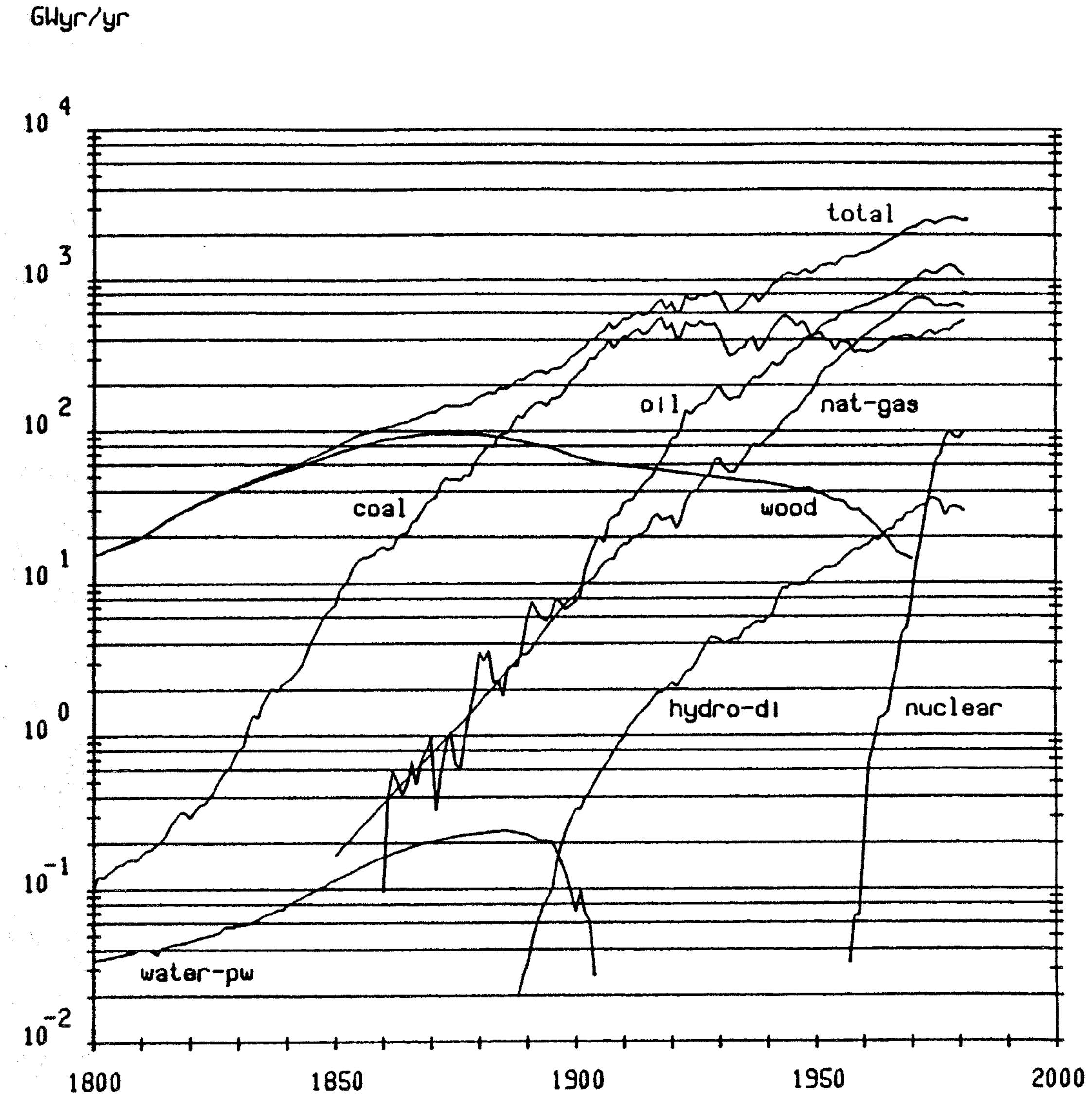


Figure 2.5 Primary Energy Consumption, US.

emerging industries. In 1880, coal supplied almost 90 percent of the fuel used for smelting iron. Thus, the end of the last century marks the beginning of the industrial development period in the United States.

The first use of crude oil and natural gas in the United States dates back to the beginning of the 19th century, and during the 1880s, reached the one-percent market share. From then on, the use of crude oil expanded somewhat faster as time

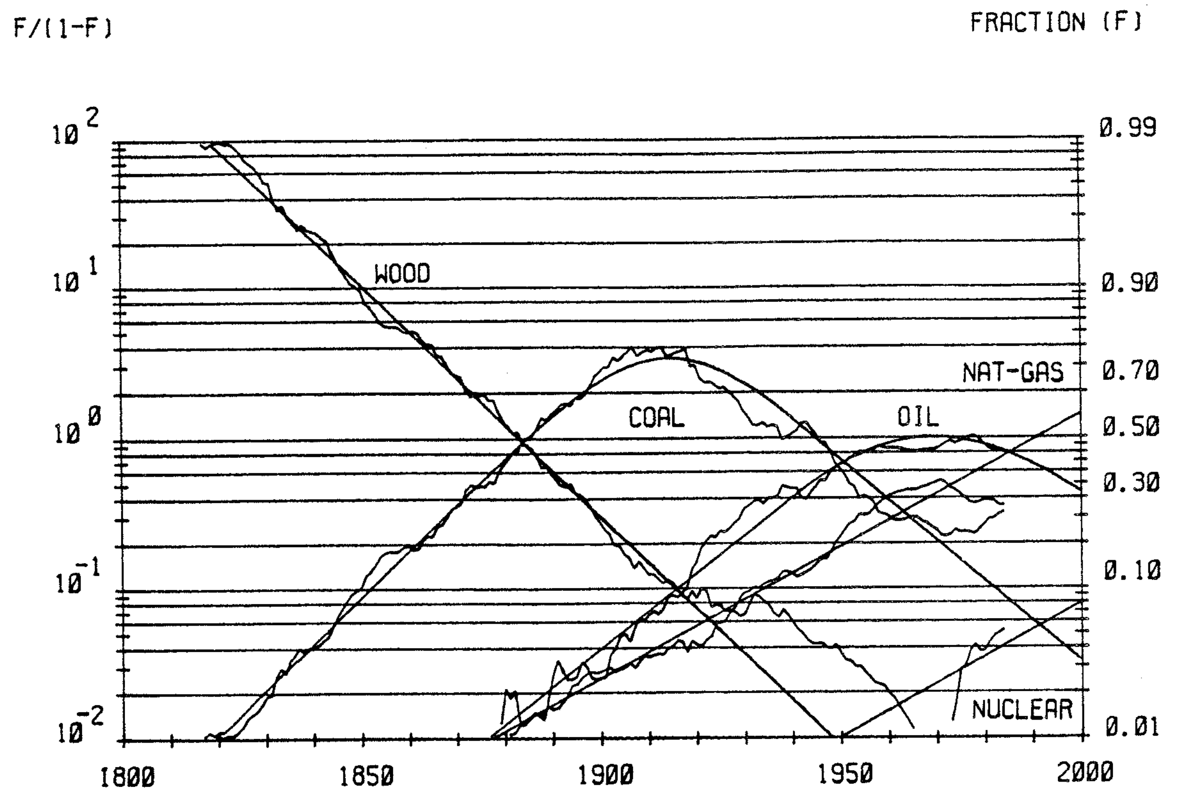


Figure 2.6 Primary Energy Substitution, US.

progressed, and by 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 more during the period of oil dominance, when compared with earlier periods. The 1950s, when oil became the dominant source of energy, represent the beginning of more intense competition between various energy sources both in the United States and in the world. Over 150 years, the energy source that dominated the contemporary energy supply also contributed more than one-half of all primary energy consumption – from 1800 to 1880, fuel wood and from 1880 to 1950, coal. During the 1970s, crude oil was close to achieving a 50-percent share, but before actually surpassing this mark proceeded to decline. Thus, during the last three decades, three important sources of energy have shared the market, without a single source having a pronounced dominance, which is contrary to the pattern observed during earlier periods. After the 1980s, Figure 2.6 shows natural gas as the dominating energy source, although crude oil still maintains about a 30-percent market share by the end of the century. As at the global level, future potential competitors of natural gas such as nuclear or solar energy have not yet captured sufficient market shares in the past 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 a slightly less than one-percent share in primary energy. Accounting for further cancellations of planned power plants and possible de-commission of those in operation and construction, we have assumed that nuclear energy could at most double its current market share at about four percent by the year 2000. This leaves natural gas with the lion's share in primary energy, advancing its position to the dominant energy source after this century.

3 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 in drilling brine wells. [2] These ancient wells were completed with percussion drills and bamboo casing. Some of the oldest wells were reported in 600 B.C. by Confucius to have reached 500 meters and to have produced natural gas which was transported in bamboo pipes for use in evaporating brine to recover salt. By the 19th century, this drilling technology improved in performance by almost an order of magnitude. Visitors to China have described drilling depths of up to 4000 meters that are comparable to the depths of many commercial wells today. In fact, some of the first natural gas discoveries in the West also were the result of drilling brine wells. Just as in China, the first significant utilization of natural gas was to dry salt, one of the largest energy consumers among the modest production processes in the pre-industrial age.

3.1 Drilling Performance and Average Depth

Modern drilling technology for oil and gas developed originally 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 United States, 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 the intensive oil drilling, especially in the United States. Probably the

2 For a more detailed overview of natural gas history see Brantly, 1971; Gaz de France, 1970 and 1971; and Peebles, 1980.

most important single innovation in drilling methods was the hydraulic rotary rig that 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 3.1,[3] which shows the drilling depth records for the three most important technologies: dry rotary and rod percussion, cable tool, and hydraulic rotary rigs. Figure 3.1 shows that both of the new drilling technologies were inferior to the older competitor in terms of record depth at the time of initial introduction. In time, however, the new technology by-passed the older 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. Starting below a thousand meters, the hydrocarbon deposits are mostly in the form of crude oil until the depth of a few thousand meters. Thereafter, the likelihood of oil deposits decreases, and below four thousand meters virtually all hydrocarbon deposits are methane or methane with carbon dioxide (see Donat, 1984). Geological evidence and chemical characteristics of hydrocarbon compounds indicate a very low probability of more complex molecules (crude oil) below these depths and an increasing probability of methane at greater depths due to high pressure and temperature (see Gold, 1985).

The technological progress in drilling expressed in terms of maximal depth indicates that new record wells, if successful, can be expected to find methane and 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 hundred years for all technologies from Figure 3.1 taken together. Figure 3.2 shows the exploratory drilling depth records in the United States, culminating with the Lone Star 1 Rogers, completed during the

3 Data sources: Brantly, 1971, and Oil and Gas Journal, 1977. Two small-diameter core test drillings in Germany were excluded from the data, one reaching 2000 meters in 1893 and the other 2240 meters in 1909, because they were not exploratory wells for commercial production of hyrocarbons.

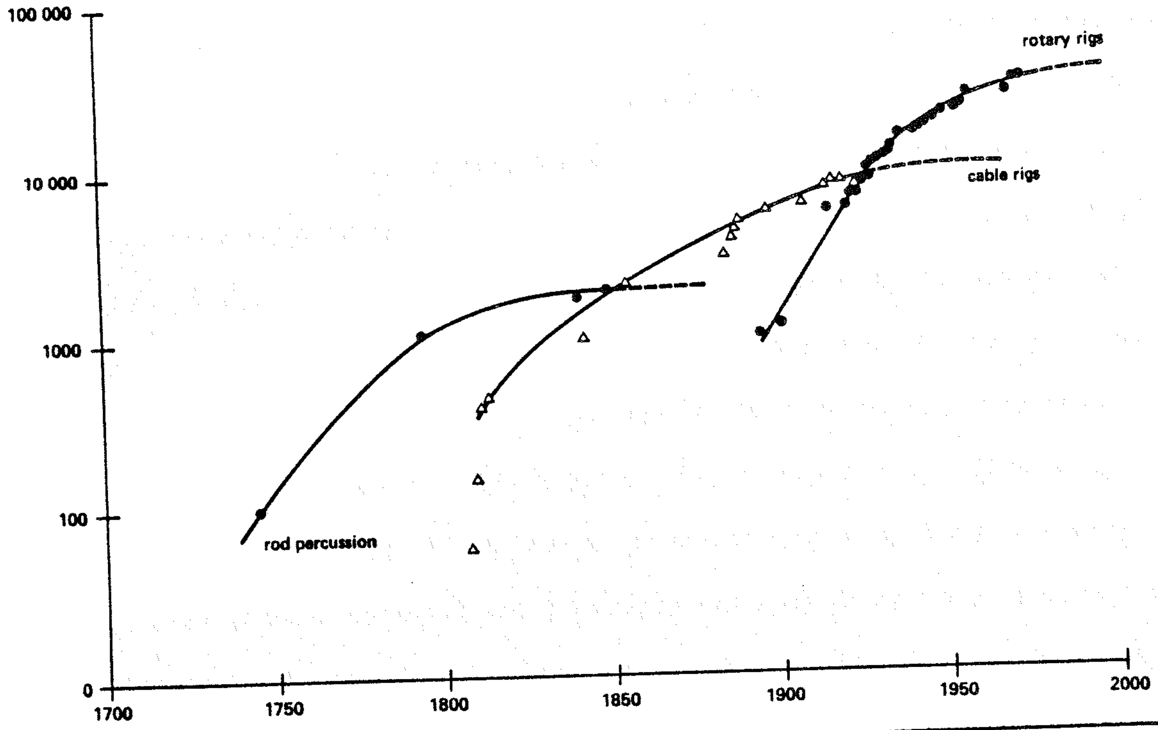


Figure 3.1 Drilling Depth Records, World.

1970s, as the deepest exploratory well drilled. This record will most likely be improved in the future. Figure 3.2 shows that the logistic trend in deep drilling would reach an asymptotic depth record exceeding 12 thousand meters. Thus, while the de-coupling of oil and natural gas technologies is not reflected in the actual 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 ten kilometers is virtually nil. In fact, most of the recent technical improvements in rigs and bits are designed for deep wells, both scientific research wells (such as the Soviet effort on the Kola Peninsula) and natural gas prospection efforts. At the same time, there is some indication that, at

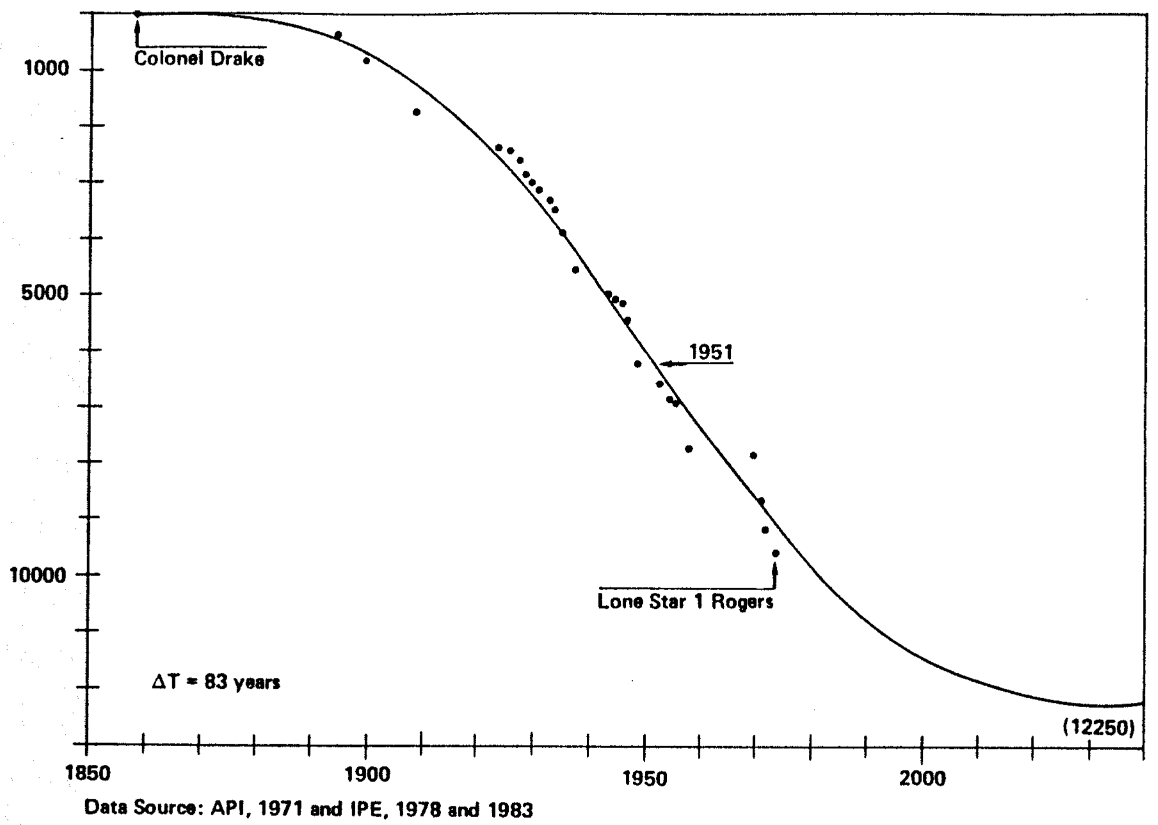


Figure 3.2 Maximum Depth of Exploratory Drilling, US.

greater depths, potentially large unconventional and abiogenic methane deposits may be found (see Gold, 1985). Thus, 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 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 3.3 shows the worldwide offshore depth records for commercial exploratory drilling. [4] Especially noticeable is the progress achieved since the first so-called oil shock of 1973. Figure 3.3 indicates that there exists a considerable potential for a further

4 Data source: API, 1986; IPE, 1983 and Ocean Oil Weekly Report, 1986.

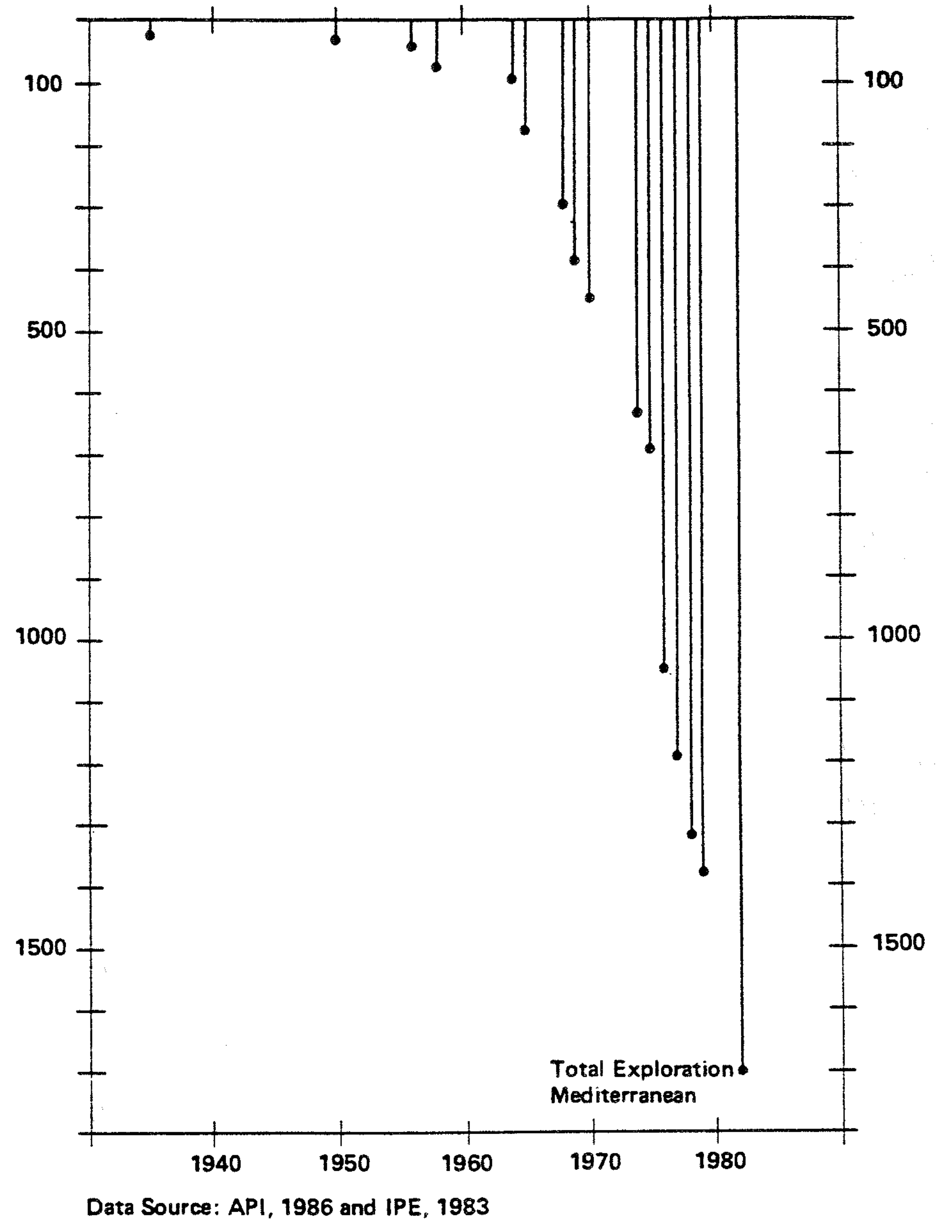


Figure 3.3 Water Depth Records in Exploratory Drilling, World.

increase in the share of offshore gas production, which currently accounts for about 20 percent of global gas production. [5]

5 Klemme, 1977, estimates that up to 40 percent of the undiscovered oil and gas reserves may be found offshore.

The evolution of exploratory drilling indicates that a long-term trend toward a higher natural gas to dry-well ratio can be observed for the United States. 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 de-coupling methane from oil technologies can be observed.

The United States is chosen primarily because of the availability of almost complete historical time series for drilling activities and because of the American technological leadership in this field since the beginning of the industry. Figure 3.4 shows the total number of exploratory wells drilled in the United States since 1900, subdivided into oil, gas and dry wells. In dealing with these statistics, it is important to observe that during the early period (i.e. before the 1920s) many natural gas finds, discovered in the course of oil exploration, may be classified statistically as dry holes due to the lack of commercial value of a great part of the discovered deposits. Despite this possible shortcoming of the official API drilling statistics, Figure 3.4 [6] indicates a large increase in the total number of wells drilled since 1900, and also large fluctuations with especially strong dips in drilling activity during the 1930s and 1960s. Figure 3.5 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 declining. Thus, the de-coupling of oil and gas technology is manifested in drilling statistics in an implicit way. Although oil wells still represent the majority of wells drilled, the number of gas wells is increasing. Unfortunately, this development was paralleled by an increase of dry

6 Source of data: API, 1971 and 1986. Alternative drilling statistics were compiled by the USGS and published in the yearly issues of Mineral Resources of the United States They indicate a much higher number of gas well drilled especially in the early period (the USGS for instance reports the cumulative number of gas wells drilled up to 1908 to amount to 21300 wells as compared to the cumulative total of 3185 gas wells as reported in the API statistics up to that year). The clarification of these differences would, however, require additional analysis. Service wells are excluded from the drilling statistics used in the examples.

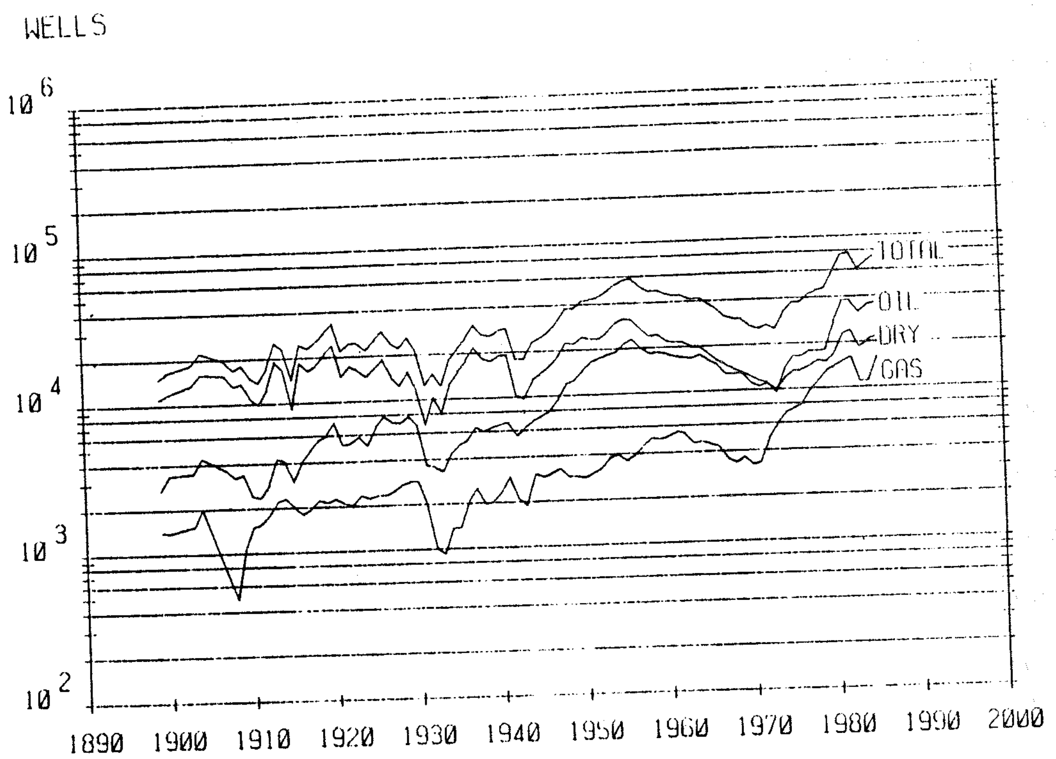


Figure 3.4 Number of Wells Drilled, US.

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 3.6 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 ten-percent market share until the 1950s, and thereafter portrays steady increases. 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 were achieved as was illustrated in Figure 3.2 (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 percent of

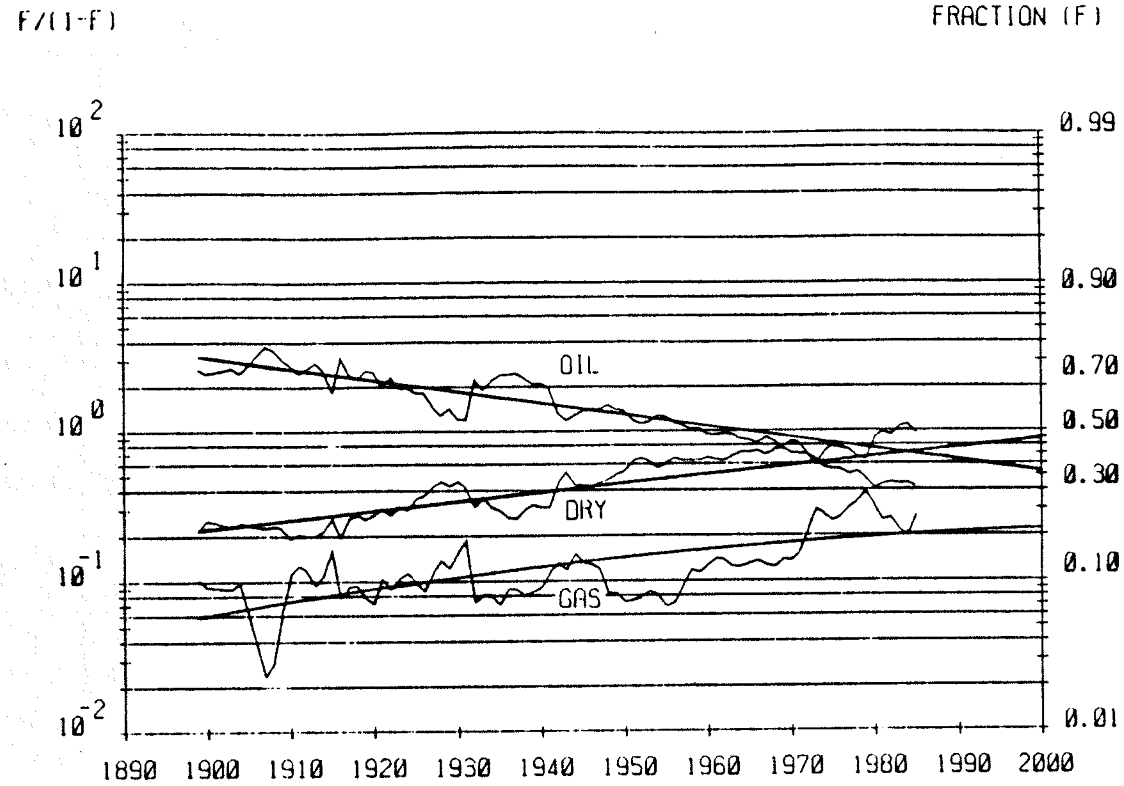


Figure 3.5 Share of Oil, Gas and Dry Wells in Total Drillings, US.

all successful wells drilled in the US will yield gas and less than 70 percent will yield oil, compared to a 10 to 90 percent relationship between gas to oil finds characteristic for 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 enhanced by the fact that the best performance in exploration wells indicates further advancement 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 de-coupling 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

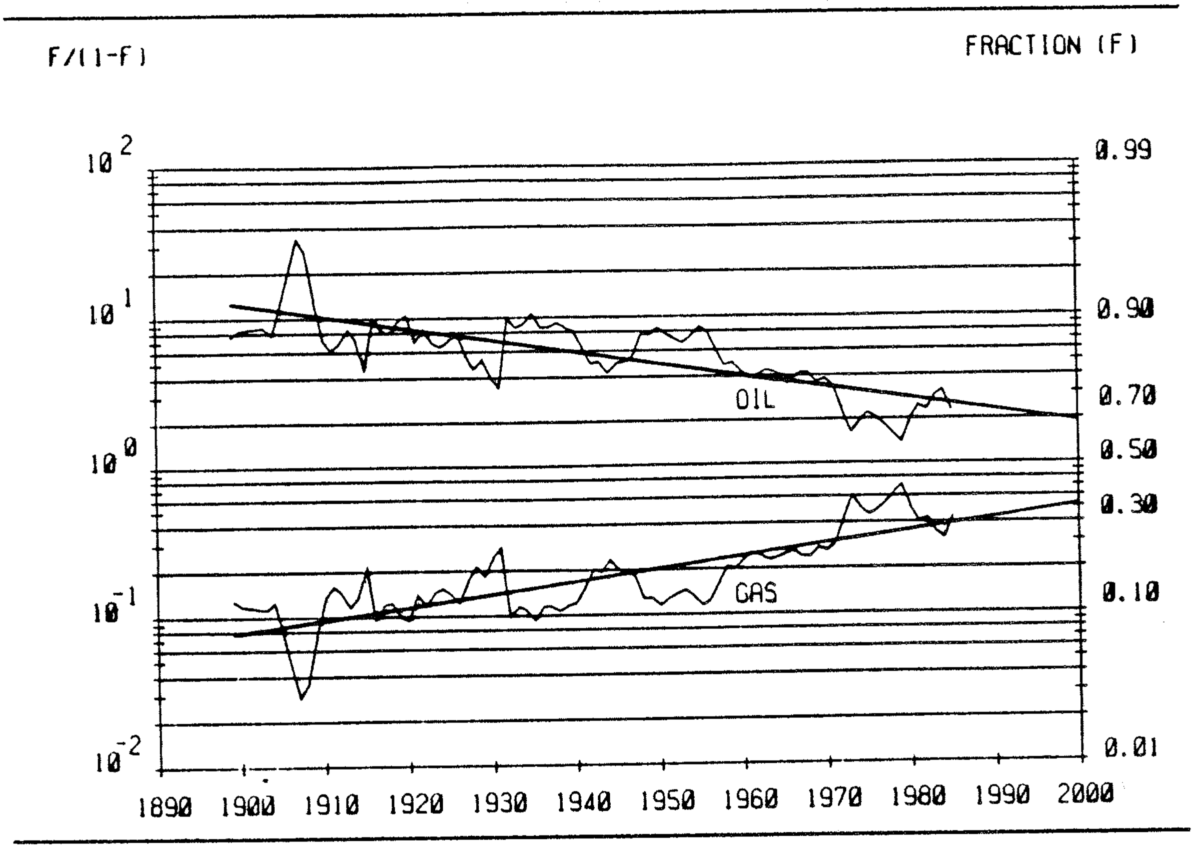


Figure 3.6 Share of Oil and Gas Wells in Successful Wells, US.

actual successful gas wells completed. Figure 3.7[7] shows a very pronounced change in the secular trend of natural gas reserve additions after the discovery of the Prudhoe Bay field in 1969 (the actual reserve additions are backdated to year of discovery). Ever since, the yield per well or per footage drilled has been considerably lower than during the 1950s and 1960s as shown in Figure 3.7. 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 3.5. It is perhaps not coincidental that this decrease or lack of improvement in exploratory natural gas drilling in the United States is

7 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 to 1979 and 1984 and API, 1986.

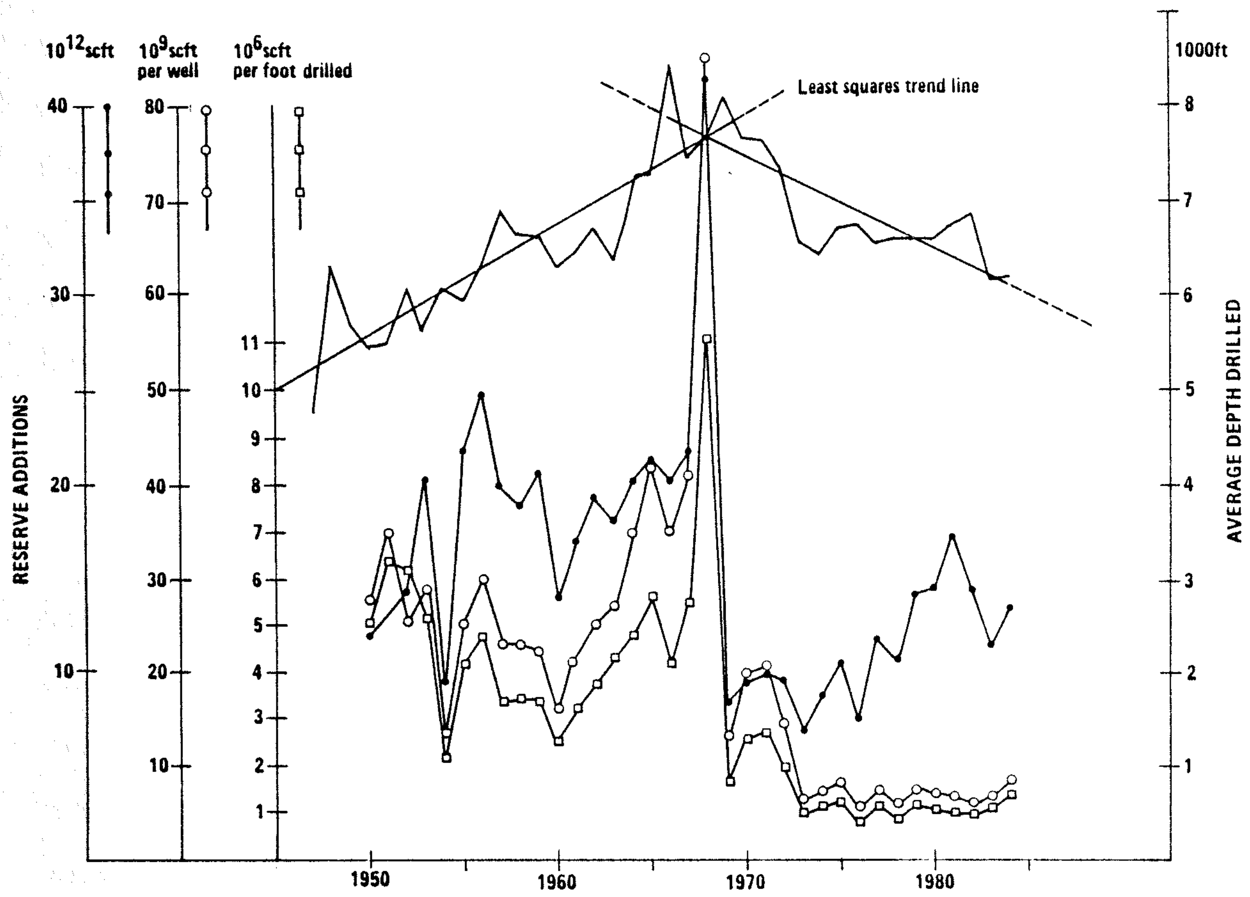


Figure 3.7 Natural Gas Reserve Additions Versus Drilling Depth, US.

accompanied by a secular trend change in the average depth drilled (see the least squares trend lines in Figure 3.7). The average depth drilled per well increased from about 5000 feet in the early 1950s to about 8000 feet by 1970. Thereafter, it has been decreasing, and currently it is slightly above 6000 feet. Considering the fact that the number of operating rigs has also decreased from about 8000 to less than 2000, it is not very likely that another trend reversal may occur in the near future.

Although it is generally dangerous to attempt an explanation based on rather sparce information, it is possible that the decrease in the yield of exploratory natural gas drilling may be simply the result of the fact that on average wells are becoming 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 1500 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 3.7 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 of deep wells (below 16000 feet) have been extremely high in the United States. 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 natural gas finding rates in the United States indicate that there is an increasing de-coupling of oil and methane technologies, although the traditional drilling technologies were practically identical whether the well was explored for oil or gas. This de-coupling 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 still is 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.

3.2 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 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 therefore 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 one-percent 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 19th 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 in general considered a waste product. By 1878, both crude oil and natural gas surpassed a one-percent 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 deposition are available only since 1935, they indicate that at that time period only 75 percent of the gross natural gas production was marketed and around 25 percent vented or flared. Natural gas waste was probably considerably higher, since not all venting operations in course of oil drilling may have been recorded. Natural gas waste decreased especially 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 and were reduced to account for less than one percent of total gross production as indicated in Figure 3.8 (data from Schurr at al., 1960 and AGA, 1972, 1975, 1979 and 1984).

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 non-associated gas, respectively) are not available for the period before 1935. [8] Figure 3.9 shows the steady increase in natural gas production from gas wells (gas

8 Hefner III, 1985, private communication, suggested that we should de-couple associated from nonassociated natural gas production in order to assess the difference, if any, between methane production from oil and gas technologies.

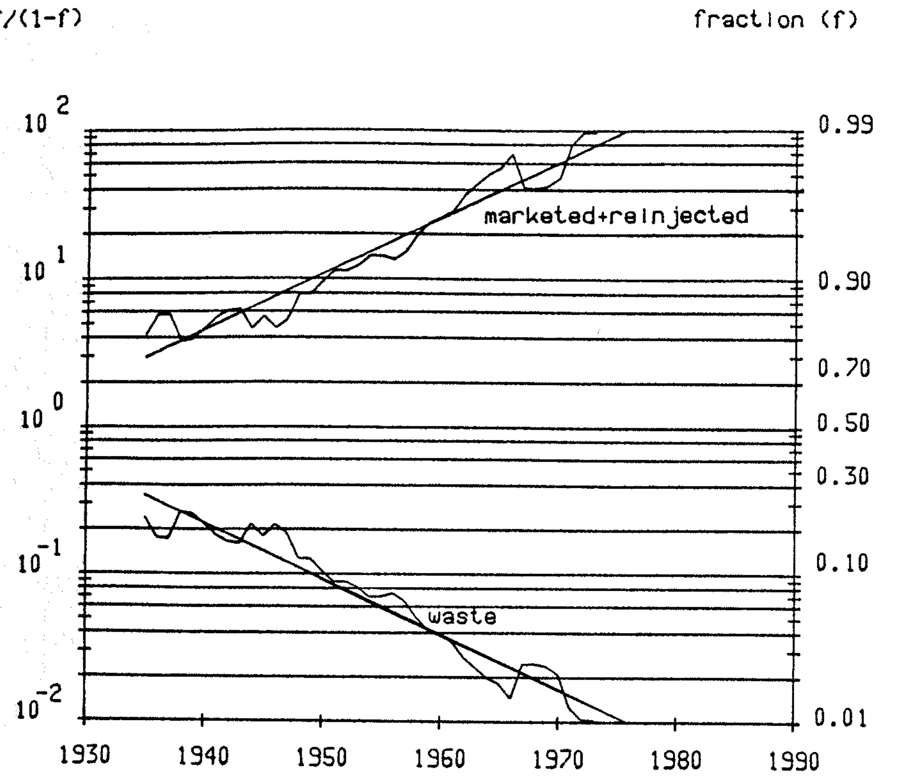


Figure 3.8 Natural Gas Deposition, US.

technology). In 1935, about 40 percent of the methane produced was from oil wells (oil technology), but Figure 3.9 shows that by the end of the century 90 percent of production should be from non-associated deposits. The decreasing shares of associated gas in total production illustrate the fact that the natural gas industry is in the process of de-coupling itself from oil. Thus, the closely related extraction, transport, conversion and end-use technologies for oil and methane may be slowly diverging on increasingly independent paths.

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 indicates that it is conceivable that the oil and natural gas industries may also de-couple downstream, going perhaps all the way to the final energy consumer. In order to investigate this possibility, we will next consider the

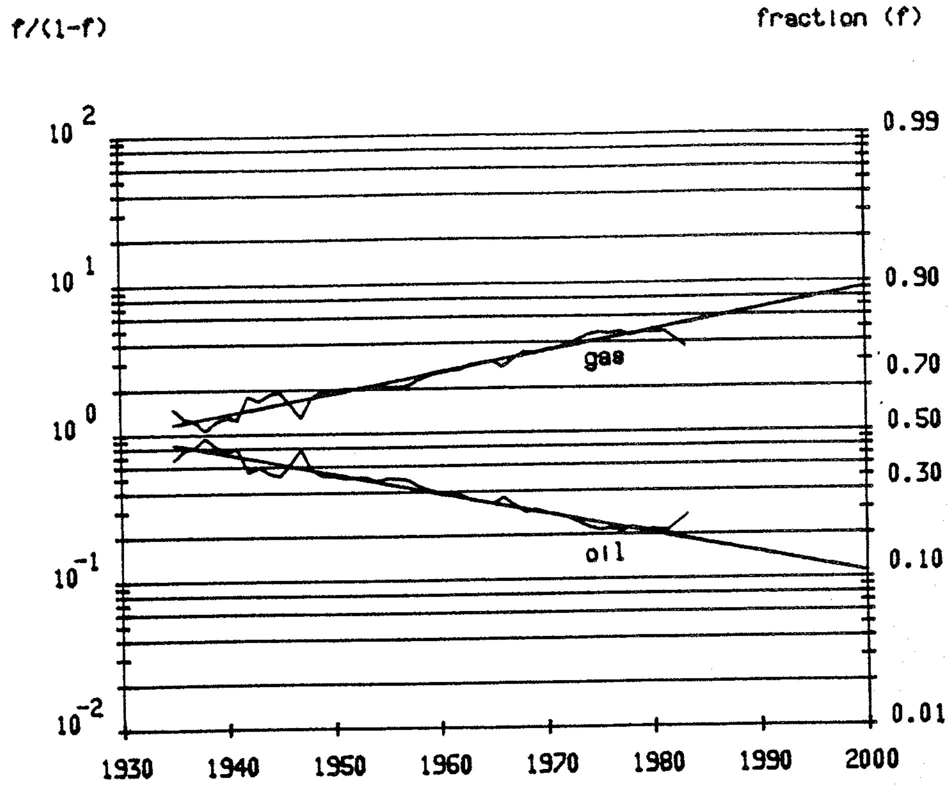


Figure 3.9 Natural Gas Production from Oil and Gas Wells, US.

evolution of different energy transport technologies and especially the development of liquid and gaseous energy transport.

3.3 Oil and Gas Transport

During the last 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. Especially crude oil, oil products and natural gas are transported by a number of different transport modes including barges, vessels, trucks, trains and pipelines.

In contrast to oil and gas transport over long-distance 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 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, but more usually coal was transported (nationwide) by barges, trains or trucks (earlier by horse wagons). Thus, the shift from wood to coal 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 United States is about 200,000 miles, slightly shorter than crude oil pipelines with 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 3.10 shows the rapid increase in pipeline length for crude oil and petroleum products in the United States.

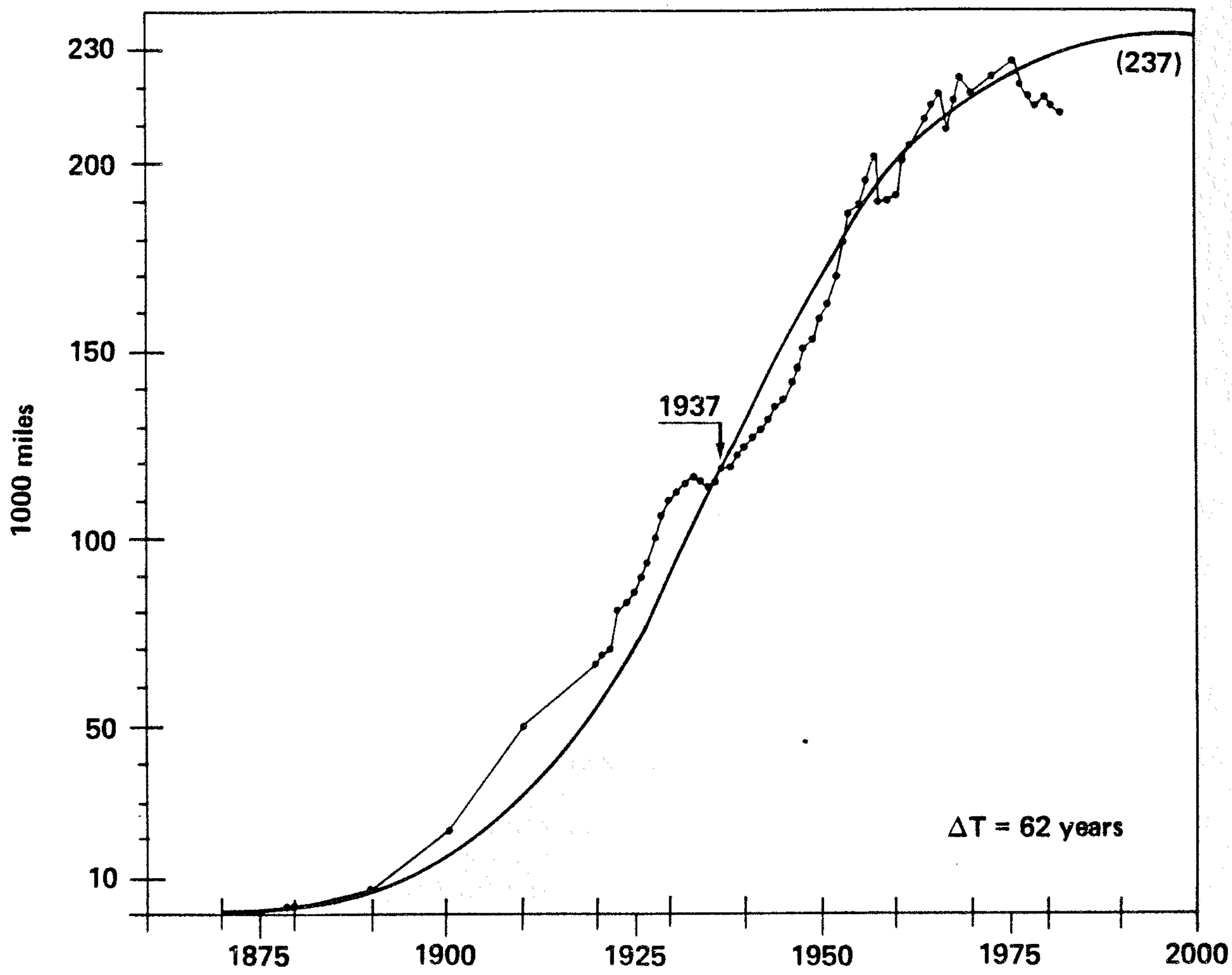


Figure 3.10 Crude and Products Oil Pipelines Length, US.

The expansion of the oil pipeline grid parallels the increase of crude oil shares in total primary energy consumption. Oil reached a one-percent 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 maximal shares in primary energy during the same decade. Thus, by 1937, about half of the current length of the oil pipeline network was already in place, and the growth rates declined slowly. During the 1980s, the length should reach the asymptotic level 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 half-way 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 3.9 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 from Figure 3.10. As mentioned above, the first natural gas pipeline in America dates back to the 1820s. 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 3.11 shows that this 20-year shift in time persists through most of the growth cycle of the natural gas transport system and distribution infrastructure.

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 to the relationship between the growth phases of oil pipelines and oil penetration in primary energy. The growth pulse started when oil achieved a one-precent share of primary energy, inflection occurred during the time when oil became the second largest energy source (by passing 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 Figure 3.11 and 2.3. The growth started towards the

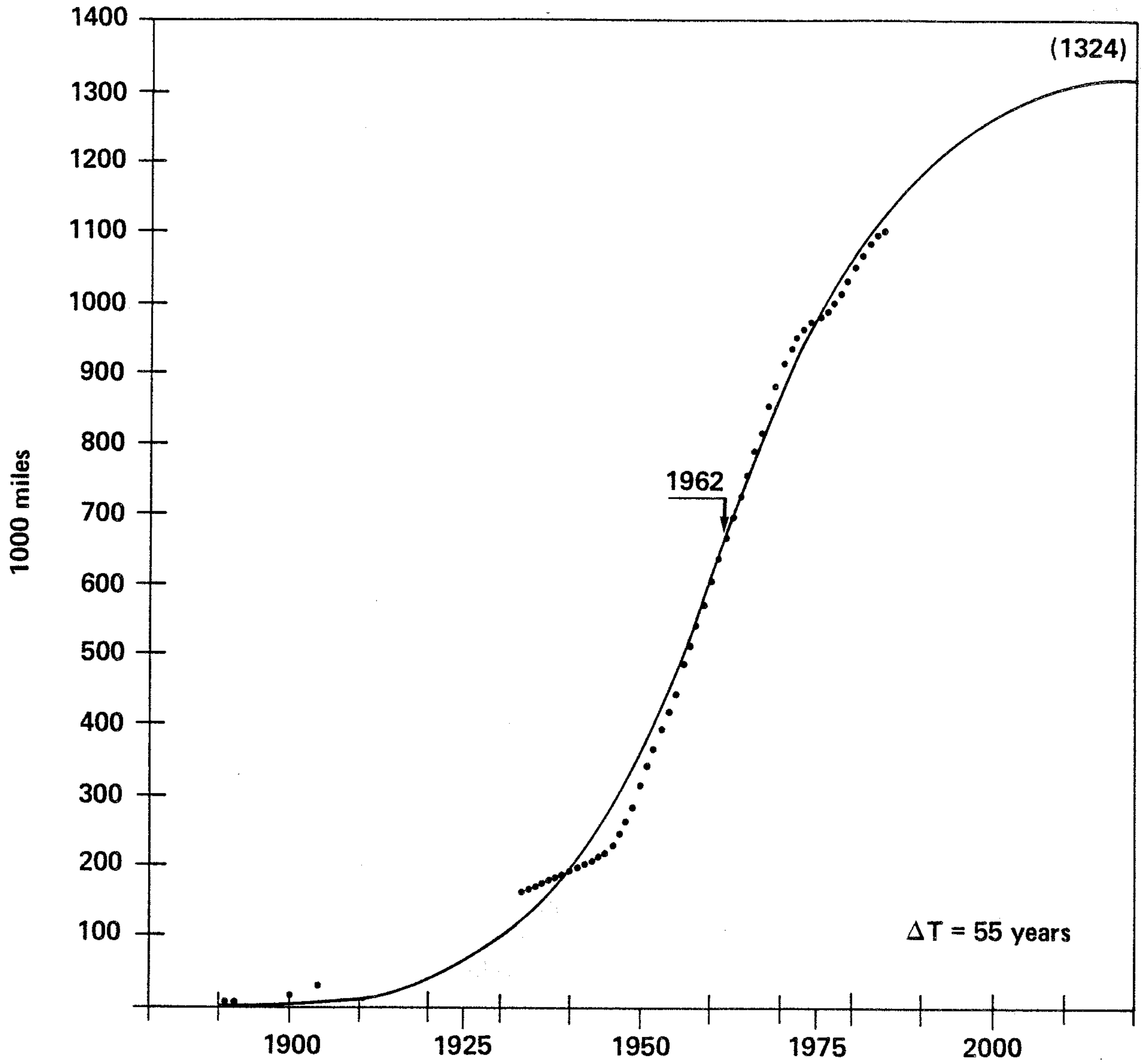


Figure 3.11 Natural Gas Pipeline Length, US.

end of the last century when natural gas achieved a one-percent share in primary energy. The inflection point was reached in 1962, when natural gas became the second largest energy source (by passing 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 3.10 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. Besides 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 of course poses the question of whether we can expect natural gas to continue to be almost exclusively transported by pipelines in the future, especially if its projected use expands as dramatically as illustrated in 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 no principal obstacles to using this transport mode for energy; the only question is whether it would be economical and competitive to do so.

This cannot be resolved here, but we mention this alternative for the future because similar solutions were found in the past to meet the ever increasing need to transport more energy over longer distances. Denser and cleaner energy forms were necessary technological measures in the past 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.

3.4 Energy Substitution and End-Use

Natural gas exploration, production and transport indicate significantly different trends from oil technologies, although natural gas was 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 portrayed 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. In order to investigate the hypothesis that natural gas is becoming increasingly de-coupled 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 3.12 shows the resulting refined version of the primary energy substitution dynamics from Figure 2.6. 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 United States for the last 190 years. Figure 3.12 represents such a higher resolution because associated natural gas (oil technology from Figure 3.9) is now

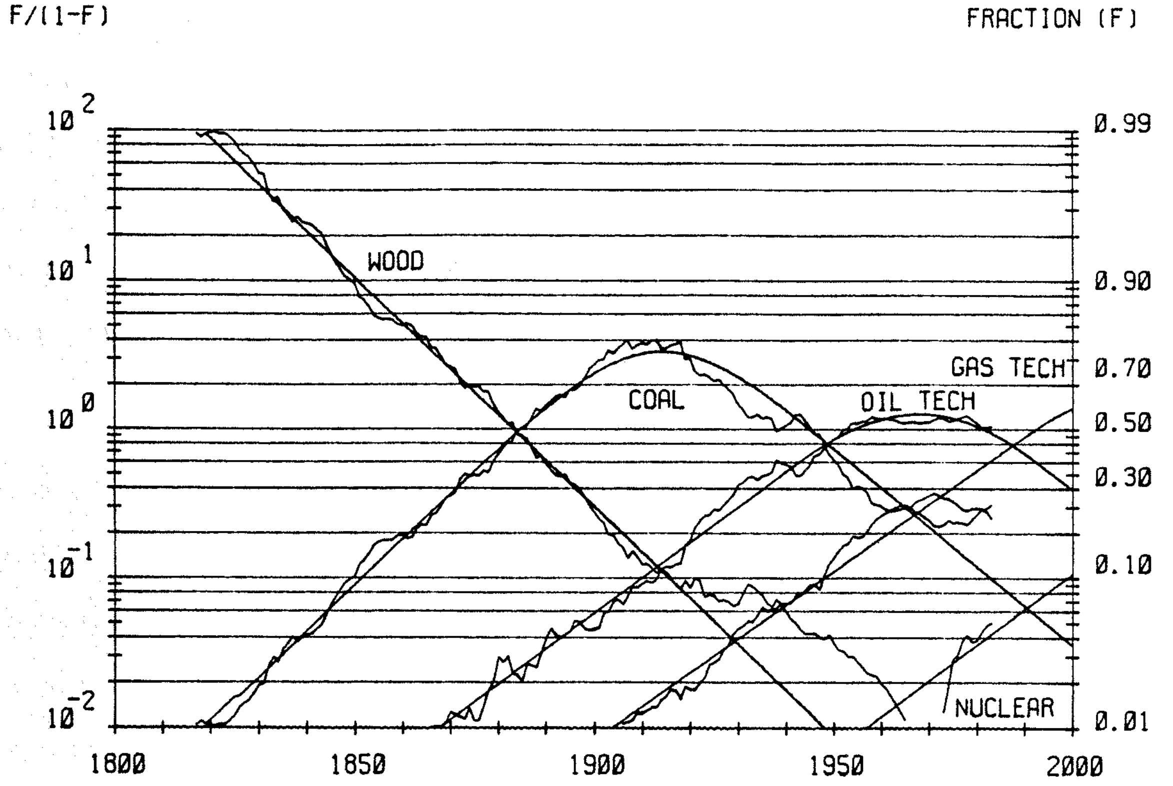


Figure 3.12 Energy Substitution and Gas Technologies, US.

reallocated to the use of crude oil and leaves the non-associated gas from gas wells 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 3.12 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 is visible 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 indicates that it is conceivable that oil and natural gas industries may also de-couple downstream, going perhaps all the way to the final energy consumer. In order to investigate this possibility, we will in conclusion 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 usually does not distinguish the actual origin of the fuel used. Thus, the difference between associated and non-associated 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 the oil and gas technology. Figure 3.13 shows the competition of different branches of the American economy for natural gas. The substitution process is very regular with modest fluctuations of actual data from model estimates. [9] 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 has indeed the characteristics of a premium fuel. Industry usually has more technological possibilities of switching between fuels and 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 more stringent

9 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, with a precision of a few percent for industry and residential sector and a precision better than one precent for the commercial sector.

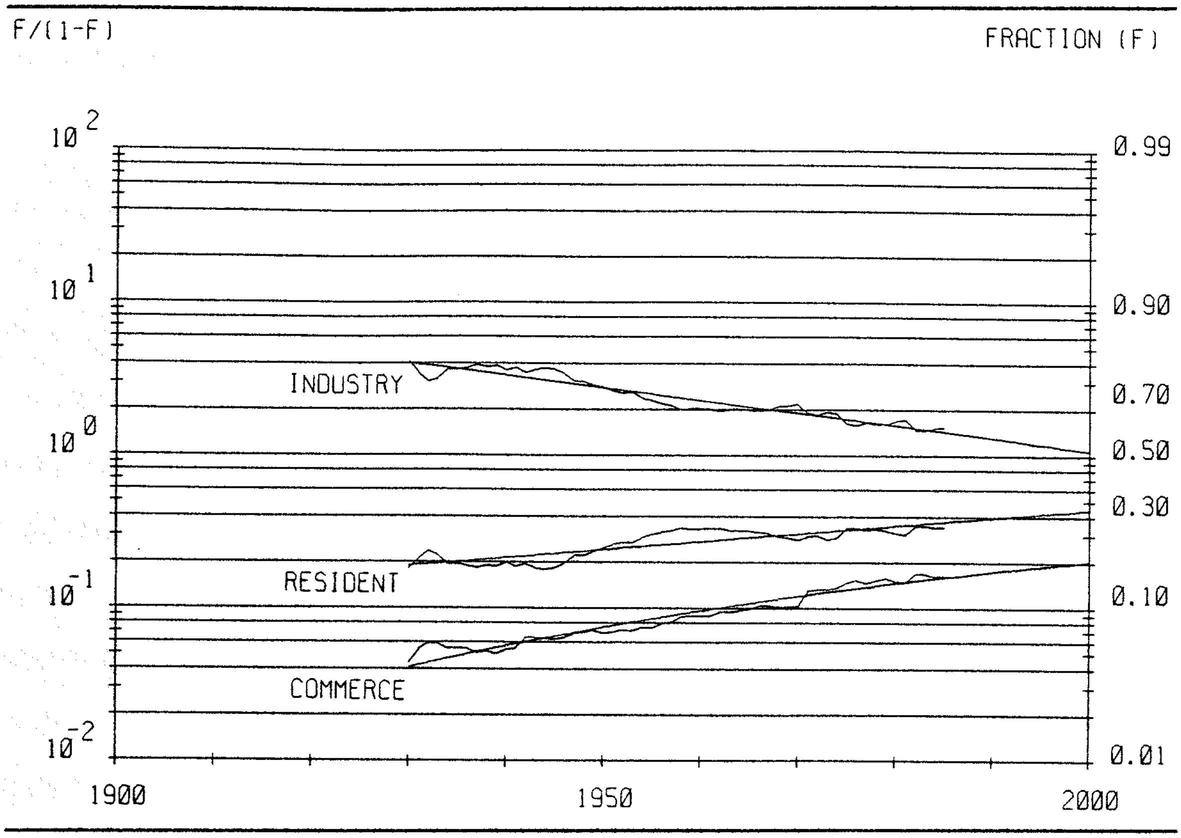


Figure 3.13 Natural Gas Use by Economic Sectors, US.

environmental controls and an increasing need for convenience in energy end-use, this trend toward larger shares of natural gas used in residential commercial sectors should be expected to continue as Figure 3.13 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 3.13 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.

4 CONCLUSIONS

In a number of examples analyzed in this paper, 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 paper, 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 in this paper are from the United States, primarily because of the American leadership in natural gas use and technologies in the past and because of the availability of data.

The refined version of the primary energy substitution in the United States, based on de-coupling oil and gas production technologies given in Figure 3.12, indicates that technological substitution can be characterized by very regular time constants provided that the historical data is accurate enough to supply the information required for further analytical resolution. In this example, the associated natural gas is reallocated to oil technology and the non-associated 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 to an eventual similar pattern of market penetration and a resulting market dominance in the next century.

Thus, in spite 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 to oil technologies which appear to be reaching saturation in the United States. It is very likely that this potential for technology improvements of natural gas 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 in the past. A prerequisite for the wide-spread use of natural gas in the future is, in our opinion, the de-coupling of methane from oil technologies, and this process was initiated long ago when associated gas supplied most of 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 both cleaner and 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, and an added 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 4.1 (Marchetti, 1982) illustrates the possibility of such evolutionary transition in the world from original reliance on fuels with relatively low to fuels with higher hydrogen content (e.g. the historical evolution of hydrogen to carbon ratio was calculated on the basis of actual energy consumption as specified in Figure 4.1 for wood, coal, oil and natural gas).

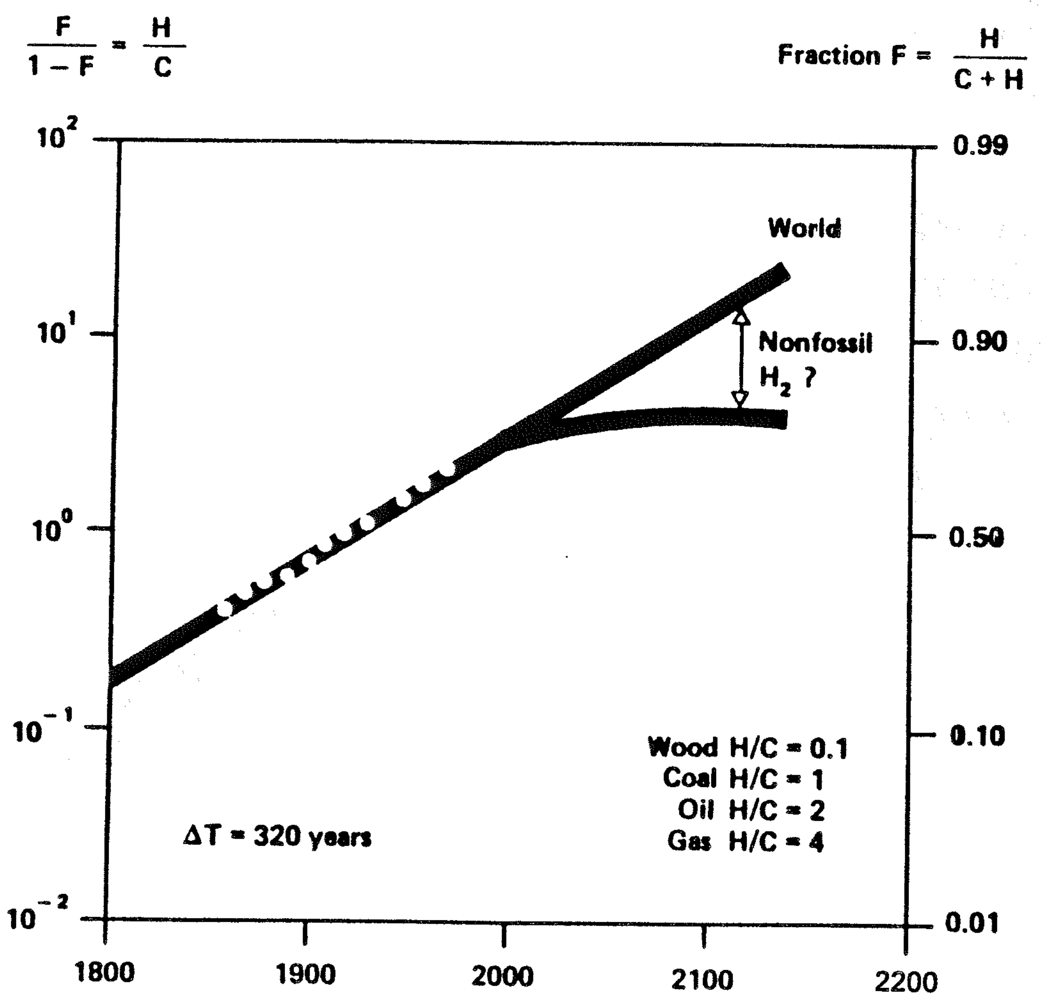


Figure 4.1 Hydrogen to Carbon Ratio of Primary Energy, World.

This transition is presented as a "substitution" process of hydrogen for carbon in the total primary energy consumption during the last century. Figure 4.1 shows that after this century the hydrogen to carbon ratio may exceed the level that can be achieved by pure methane economy (this level is indicated by the curve that levels off in Figure 4.1) implying that some additional hydrogen could be needed to supplement the increasing reliance on methane, if the historical trend of increasing hydrogen to carbon ratio should prevail in the future. 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.

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