Global Natural Gas Perspectives

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Foreword

On the occasion of the IGU Council Meeting in Kyoto, Japan during the week of October 2-5, 2000, I'm very pleased to have this opportunity to provide our IGU Council Members and Member Associations with the recently completed Report: "Global Natural Gas Perspectives" by Dr. Nebojša Nakićenović, and contributing authors, Mr. Andrei Gritsevskyi, Dr. Arnulf Grübler, and Mr. Keywan Riahi of the International Institute for Applied Systems Analysis (IIASA) in Laxenburg, Austria.

By way of a brief introduction, I would like to mention the following. Dr. Nakićenović has been affiliated with IIASA since 1973 and was the Project Leader of the Environmentally Compatible Energy Strategies Project at IIASA from its establishment in 1991 until earlier this year when he assumed the leadership role for IIASA's new Transitions to New Technologies (TNT) Project. He is well-known as the author and co-author of many scientific papers and books on the dynamics of technological and social change, economic restructuring, mitigation of anthropogenic impacts on the environment, and on response-strategies to global change and he has served as a Lead Author of the Intergovernmental Panel on Climate Change (IPCC) Technical Report on "Technologies, Policies, and Measures for Mitigating Climate Change," a Convening Lead Author for Working Group III of the IPCC, a Member of the Energy and Environment Steering Committee of the World Bank, and an Advisor to the United Nations on Sustainable Development.

This week we are very fortunate that Dr. Nakićenović has agreed to be our guest and to make a presentation based on his Report and his recent work on developing emissions scenarios for the IPCC's new study published earlier this year. I very much hope that you will find this work, and the presentation, to be a valuable – and, perhaps, even provocative -- new perspective for our discussions on the future of natural gas based technologies and on how IGU can best promote the technical and economic progress of the world-wide natural gas industry to ensure that gas does, in fact, realize its full potential as the energy for the 21st century.

Hiroshi Urano
President
International Gas Union

Abstract

The provision of adequate energy services is a prerequisite for further social and economic development in the world. This is a formidable challenge for the 21st century. Median demographic projections indicate that the global population will increase to ten billion by the end of the 21st century. At the same time, an important priority is to improve the quality of life for many now excluded from the commercial economy and commercial provision of energy services. It is estimated that about two billion people do not have access to commercial energy. Thus, some six billion people will need to be "connected" to the global energy system during the 21st century, a number equal to the current global population. Natural gas and other energy gases can make a substantial contribution to fulfilling this challenge during the 21st century. The objective of this paper is to assess long-term global natural gas perspectives, the opportunities that they offer and the challenges that exist in view of competing alternative energy options. These long-term perspectives are intended to help set the stage for energy policy decisions to be made over the next several years.

The most recent findings indicate that perceptions about global methane resources have changed drastically. Natural gas is much more abundant around the world than was estimated just a decade ago. In fact, new discoveries have by far outpaced increases in global consumption. Resources of conventional and unconventional gas continue to be revised upwards. In addition, the more speculative occurrences of natural gas, such as methane hydrates (clathrates), are truly vast and, if ever commercially exploited, could supply any conceivable future energy demands for centuries to come. This study documents the most recent findings about global hydrocarbon resources and highlights the potential future role of natural gas and other energy gases, such as hydrogen, that can be produced from methane, the main constituent of natural gas.

The global energy system has evolved during the last two hundred years from a reliance on traditional energy sources based first on coal, then oil and more recently on increasing shares of natural gas. Other energy sources play a smaller role by comparison. This has resulted in a substantial "decarbonization" of the global energy system, namely, the reduction of the amount of carbon per unit energy or carbon-intensity of energy. The study describes this historical transition from a carbon-intensive to less carbon-intensive energy structure and assesses possible future developments and their implications for natural gas.

Natural gas is the only hydrocarbon source of energy that could both lead to further decarbonization in the world and to a reduction of the many adverse impacts energy use has on the environment and human health. Furthermore, natural gas could be the bridge to carbon-free energy sources, such as solar or fusion energy, or even hydrogen

extracted from the vast clathrate resources. Decarbonization of methane from clathrates, and other gas sources in general, will require the development of new technologies for carbon sequestration and storage. This study reviews some of the innovative schemes that could be developed in the future to produce carbon-free energy gases and other energy carriers such as electricity.

Thus, natural gas appears to be ideally suited to provide a bridge from the current energy system to the new era of more environmentally sound energy systems. It can help achieve two important energy goals for the 21st century – supplying the energy services needed for social and economic development and reducing adverse impacts on the environment at all scales. This, however, requires the emergence of large-scale interconnected energy grids throughout the world and especially in Eurasia where the largest increases in energy services are expected. Such a development implies a drastic energy-geopolitical shift. This study assesses the possibility of new energy grids and various implementation strategies that could lead to lower carbon intensities in the world, and lower adverse environmental impacts of energy at all scales.

Thus, natural gas holds great promise as an energy source of choice for the 21st century. It is the cleanest of all the hydrocarbon energy sources, it has high conversion efficiencies and it is likely to be available for a very long time to come. The challenge over the next several years will be to translate this promise into practice.

Introduction

Natural gas holds the promise of providing for human energy needs during the 21st century and well beyond. It could become the bridge for a transition to an era of affordable, abundant, pervasive and clean provision of energy services throughout the world. Today, two of the six billion people in the world do not have access to modern and affordable energy and it is widely acknowledged that the provision of energy services is a fundamental prerequisite for development, prosperity and the eradication of poverty in the world. According to median demographic projections, global population is likely to increase by some four billion people during the 21st century. Thus, some six billion people will need to be provided by affordable and clean energy services, a number equal to the current global population. This additional need for energy services is voracious and will not be satisfied with the current structure of the energy system, with current technologies and certainly not with the current adverse impacts associated with energy, from indoor air pollution and regional acidification to climate change. In conjunction with new and advanced technologies, natural gas can provide for a large part of the rapidly growing need for clean and affordable energy services. This is the major challenge and a great opportunity to pave the way for a more prosperous future with less human intrusion on nature and interference with planetary processes such as climate change.

The perception of natural gas availability has changed dramatically during the last decades. The traditional view is that conventional reserves of natural gas in the world are limited, say to some six decades at current consumption levels. This is strictly speaking still correct. However, this is a static view that is challenged by many recent assessments. It is now quite widely accepted that natural gas resources are quite abundant and more widely distributed than those of oil. The main issue is which portion of the resources could be extracted with conventional methods and current prices and which portion would require advanced and new technologies at competitive costs. As technologies improve and market conditions change, some resources are transferred (reclassified) into what we consider to be the reserves. Thus, reserves are really a dynamic construct, always being replenished from the resources as gas demand and the gas industry evolves. In fact, the historical growth of reserves, often shown as a reserves-to-production ratio, has exceeded increases in consumption. Another important development is that some of the so-called unconventional sources of methane (the main constituent of natural gas) are becoming competitive, such as extraction from coal beds. The most drastic change in perception is associated with gigantic quantities of methane trapped in ice, the so-called methane hydrates (clathrates). Some estimates indicate that this form of methane might represent an energy resource far larger than all other known hydrocarbon energy resources put together. The challenge is to understand the conditions that would make some of these enormous resources become future reserves that could be successfully exploited. Carbon dioxide clathrates could also provide for the possibility of storing sequestered carbon in the future and the extraction of methane from clathrates might also help promote the technological development required for carbon storage.

The conversion of natural gas into electricity and heat is very efficient in comparison with other hydrocarbon energy forms. Combined-cycle natural gas power plants are more efficient than any other commercial thermal-electricity conversion technology. The efficiency of producing heat with natural gas is very high and combined heat and power cogeneration and other "polygeneration" schemes, represent a further reduction of specific energy requirements for the provision of energy services. At the same time, electricity from natural gas is more competitive than other options where natural gas is available, e.g., where transport and distribution infrastructures exist. In fact, it is usually the cheapest and preferred source of electricity. Capital costs are much lower compared to other options and this is especially important to gain a competitive edge in privatized and deregulated energy markets. There are many advanced technologies that might provide even more efficient natural gas conversion and end use in the future. Fuel cells, mini and micro turbines, conversion of gas to liquids and production of hydrogen with carbon removal and storage are all options that are likely to diffuse in many parts of the world during the 21st century thus making natural gas even more competitive, more reliable and even more broadly available.

To be successful, all of these future energy options and technologies need to be aggressively developed and deployed and will require both private and public investments. This also holds true for other advanced technologies: hydrocarbon energy sources, renewables and, where appropriate, also nuclear power will not become commercially viable and attractive unless there is a great improvement in their technical and environmental performance, universal availability and perhaps foremost a significant reduction of costs. The current advantage of natural gas is that combined-cycle gas-turbine is such a technology: its performance improved and its costs declined dramatically during the last three decades. However, developments are underway that might change this situation, for example, by radically reducing the costs of renewables or the adverse environmental impacts of coal. This further indicates the need to improve current and develop new natural gas technologies.

Natural gas is the cleanest of all hydrocarbon energy sources. Natural gas burns clean and has very low emissions of pollutants such as particulate matter, carbon, sulfur and nitrogen oxides even with current technologies. For example, it results in less than half the carbon dioxide emissions compared with coal. It has very little, if any, sulfur as an energy carrier so that its combustion products are essentially free of sulfur oxides. High-temperature combustion does lead to emissions of nitrogen oxides. Modern combustion technologies are however designed to limit the formation of these compounds and usually result in acceptable low emissions levels. With the diffusion of advanced technologies, natural gas use could become virtually emissions free. New technologies for converting natural gas into electricity and other energy forms hold the promise of reducing and virtually eliminating most adverse environmental impacts.

The issue of carbon dioxide and other greenhouse gas emissions that are associated with anthropogenic climate change is somewhat more complex. Carbon is oxidized during the combustion of natural gas which inherently leads to emissions of carbon dioxide. However, there are methods to sequester the carbon before and after combustion. This would require some form of carbon storage over millennia. Therefore, many such decarbonization strategies favor natural gas because it has the lowest carbon content of all hydrocarbon sources of energy and would consequently require lower sequestration efforts. At the same time, natural gas consists mostly of methane, a gas with a very strong greenhouse effect, so that avoidance of these emissions is of great importance and needs to be an essential component of energy decarbonization strategies.

A Brief History of Natural Gas

Born in the East

Natural gas has been used since antiquity. “Eternal flames” emanating from the ground, in areas known today as prolific petroleum and gas provinces, were used for religious veneration and have been documented in numerous reports by historians. The gas fires of Baba-Gugur (Kirkuk, Iraq) are described both by the Greek historian Plutarch and the Arab historian Massoudi. Gas fires on the Apsheron peninsula ashore the Caspian sea (Baku) have also been reported since antiquity (Gaz de France, 1970 and 1971). The same region also gave birth to the cult of Zarathushtra (Zoroaster), in which the worship of fire played a central role. Parsi (Zoroaster’s followers in India) merchants constructed the Ateshgyakh fire-worshipper’s temple in Surakhany in the 17th century, and its eternal flames were fuelled by natural gas well until the end of the 19th century. Figure 1 illustrates how the temple might have looked and shows its eternal flames. The Nobel brothers are reported to have purchased some of their concessions from the last priests of that temple. Baku became the largest oil producing and exporting region in the world at the beginning of the 20th century and with new discoveries promises to grow as a major global supplier during the 21st. Today, the fires from gas flares atop the oil fields have replaced those of the Ateshgyakh temple.

Figure 1: Drawing by a 19th century artist (left) and contemporary reconstruction (right) of the Ateshgyakh, or fire-worshipper’s, temple close to Baku, Azerbaidjan. The eternal flames of the temple, fired by natural gas, are reported to have burned for centuries, testimony of ancient knowledge about existence and possible uses of natural gas. Source: Baku Pages, 2000.

The earliest, larger scale, use of natural gas for energy purposes occurred in China. Detailed reports appeared in Western literature during the 18th century and the practice and technologies used have been well documented (Brantly, 1971). For example, drilling wells for water, brine and gas were reported by Confucius to have reached depths of 500 meters (m) by 600 B.C. By the 19th century western visitors to China reported drilling depths of up to 4,000 m, comparable to the depth of many commercial gas wells today. Frequently, natural gas was found when drilling for brine where the gas was used to evaporate the brine to obtain salt. In some instances, the gas was transported by bamboo pipelines to other centers of consumption as illustrated in Figure 2. This pattern of gas finds and use in association with brine can also be observed for the earliest uses of gas in North America in the first half of the 19th century. The commercial use of natural gas thus pre-dates the beginnings of the modern petroleum industry in the second half of the 19th century.

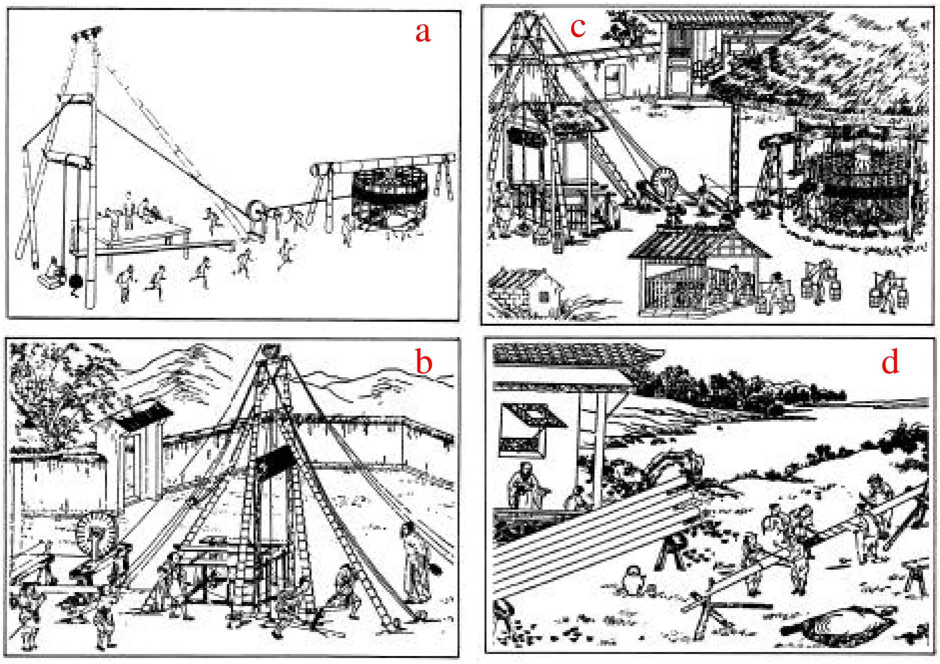


Figure 2: 18th century Chinese sketches explaining major steps in drilling for brine (and natural gas). (a) Springpole precussion drilling; (b) well casing with bamboo; (c) pumping of brine; (d) bamboo pipeline construction for gas transport. Source: Revue de l'Energie, 1984.

Moving West

The history of gas production and use in the industrial era is dominated by the US, which accounted for well over 95 percent of global gas production and use well into the 1930s. After originating in the East, the gas industry was thus reborn in the West. The earliest recorded commercial natural gas use in North America is reported to have started almost two centuries ago. In 1821, natural gas was used for lighting in Fredonia in New York State (Schurr and Netschert, 1960). This was when coal supplied just a mere one percent of the primary energy use of the US, the remaining 99 percent being supplied by fuel wood. Natural gas continued to be used sporadically throughout the 19th century, but in the absence of an appropriate infrastructure (e.g. bamboo pipelines) found only limited markets (e.g., brine evaporation, production of carbon black). The first US gas pipeline was constructed in 1883 (to Pittsburgh). By that time both oil and gas supplied about one percent of the US primary energy needs and their market shares expanded rapidly thereafter. By 1900, the US produced some 10 billion cubic meters (10 Gm^3 or about 370 PJ), a production volume that increased tenfold by the early 1940s. The growth of the US gas industry was basically synonymous with that of the global gas industry prior to Second World War. The US accounted for well over 90 percent of global gas production and use well into the early 1950s (Grübler and Nakićenović, 1988).

Stepsister of Oil

The close association of the early gas industry to oil is the result of geology. With the development of oil in the last decades of the 19th century, large amounts of associated gas – considered more often a nuisance rather than an asset – were produced. It is fair to say that historically gas is the “stepsister of oil.” In the absence of market outlets, associated gas production was simply vented or flared. The emergence of gas produced as fuel in its own right (unassociated gas) is much more recent. For example, in the US, unassociated gas surpassed the one percent share of primary energy use only in the first decades of the 20th century (Grübler and Nakićenović, 1988). By that time, more than half of all the associated gas produced went unutilized, originally being either vented or flared, only later on to be increasingly reinjected into oil fields. Half of the produced gas was unutilized in the OPEC countries up to the early 1970s (CEDIGAZ, 1998). The both economically and ecologically doubtful practice of gas flaring peaked at some 210 Gm^3 (7.7 EJ) in 1973 globally, but continues until today. In 1997 some 120 Gm^3 (4.4 EJ) were flared resulting in luminosity easily discernible from night satellite imagery as shown in Figure 3. Thus, even today a large portion of produced gas is either wasted or remains unused. Figure 4 shows that about 20 percent of global gas production was not used in 1997.

Methane as a Global Energy Source

Although natural gas has been used since antiquity, it has not played a major role in the global energy system until recently. Global energy use has evolved from a reliance on traditional energy sources such as fuel wood and coal, and then oil and natural gas, and more recently, but to a significantly lesser extent, on nuclear and hydroelectric energy sources. Consistent with this long-term transformation and structural change in the energy system, is the shift to methane as less carbon-intensive and perhaps even carbon-free energy source for the 21st century.

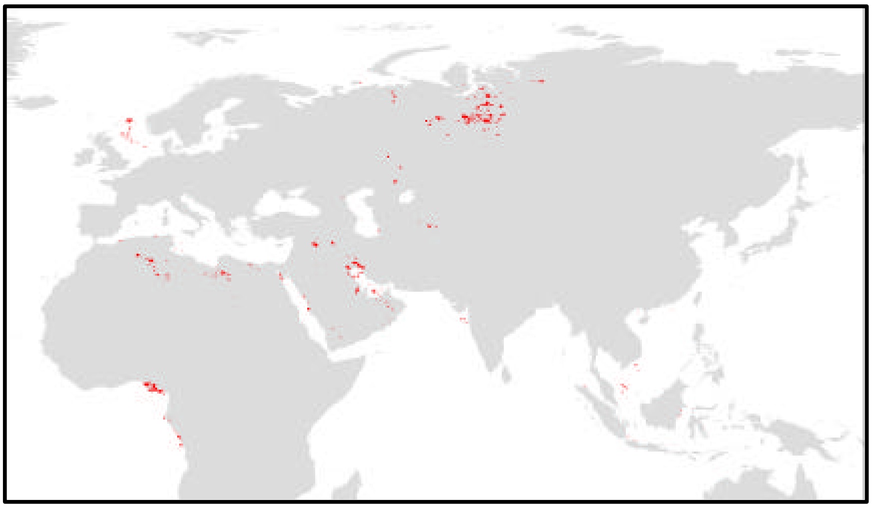


Figure 3: Flaring of natural gas in oil fields as identified in night satellite imagery. All other light sources, most notably human settlements have been filtered out. Source: Defense Meteorological Satellite Program, NOAA; picture courtesy of C. Elvidge, see Elvidge *et al.,* 1997.

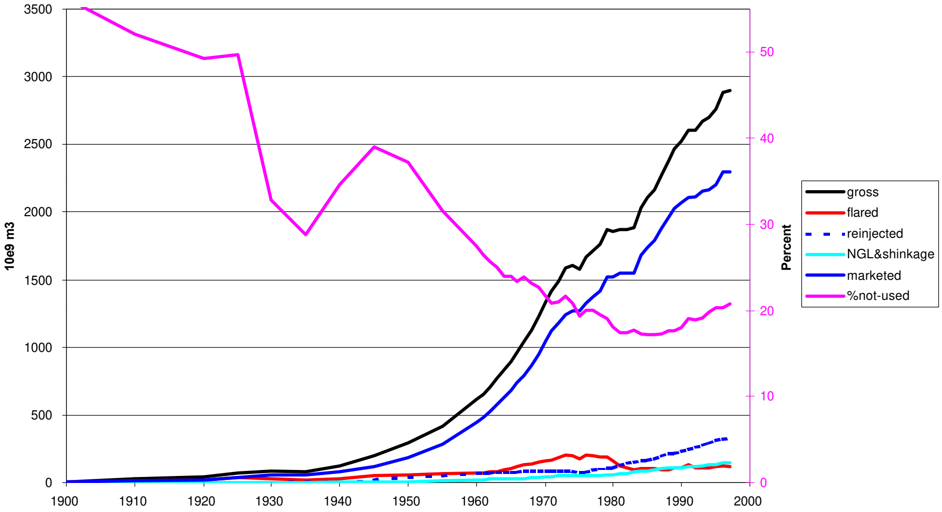


Figure 4: Global natural gas disposition since 1900 (in billion cubic meters). Source: Grübler and Nakićenović, 1988, updated from CEDIGAZ, 1998.

Figure 5 illustrates the evolution of the global primary energy supply since 1850. The contribution of gas grew only modestly prior to the 1940s, but then experienced rapid expansion during the following three decades. Throughout its history, the market share of gas has been determined by infrastructural bottlenecks rather than by the availability of exploitable geological deposits.

The fact that the Caspian continues to hold significant reserves of oil and gas after being an extremely prolific source of hydrocarbons for more than a century, and promises even more in the future, should cast doubts on a pending early end of the hydrocarbon era. This especially holds true for natural gas, as its share in cumulative past production is small, but remaining reserves are extremely large and are still expanding.

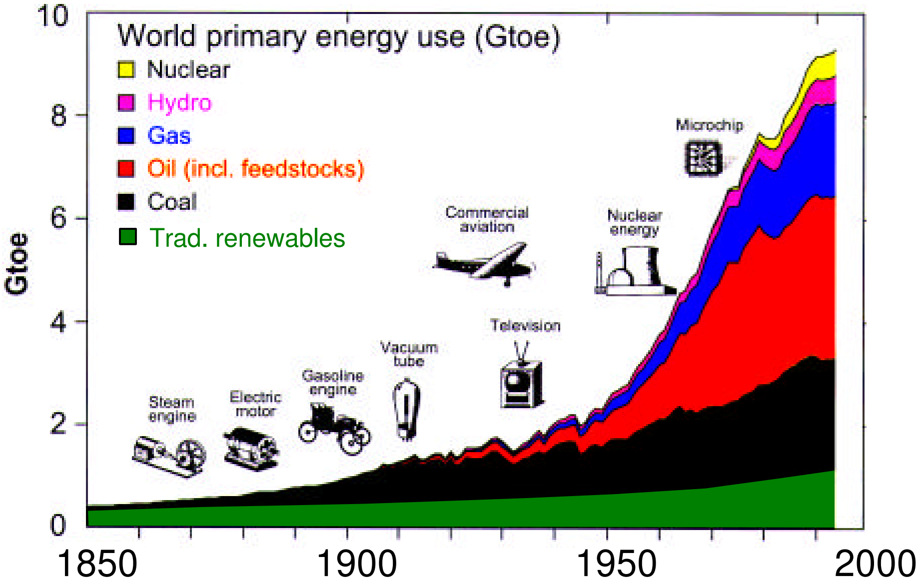


Figure 5: Global primary energy consumption by source, historical development from 1850 to 1990, in EJ. Source: Marchetti and Nakićenović, 1979; and Grübler, 1998.

Decarbonization of Global Energy

Carbon Intensity

The increasing share of methane has been one of the reasons for the decreasing carbon intensity of energy. One way to measure the carbon intensity of energy is by the ratio of carbon to hydrogen atoms of hydrocarbon fuels. Hydrocarbon energy forms consist of molecular compounds that include carbon and hydrogen atoms. Wood has the highest effective carbon-content, with about ten carbon atoms per hydrogen atom. If consumed through deforestation (i.e., without the compensating carbon absorption through biomass growth), wood produces higher carbon emissions than any other hydrocarbon fuel per unit energy. Among fossil energy sources, coal has the highest carbon-to-hydrogen ratio, roughly one to one. Oil has on average one carbon for every two hydrogen atoms, and natural gas, or methane, has a ratio of one to four.

Decarbonization can be expressed as a product of two factors – carbon emissions per unit energy and energy requirements per unit of value added, called energy intensity. As Figure 6 shows, the ratio of carbon emissions per unit of primary energy consumed globally has fallen by about 0.3 percent per year since 1860. The ratio decreased because high-carbon fuels, such as wood and coal, have been continuously replaced by those with lower carbon content, such as gas, and also in recent decades, albeit to a much lesser extent, by nuclear and renewable energy, which contain no carbon.

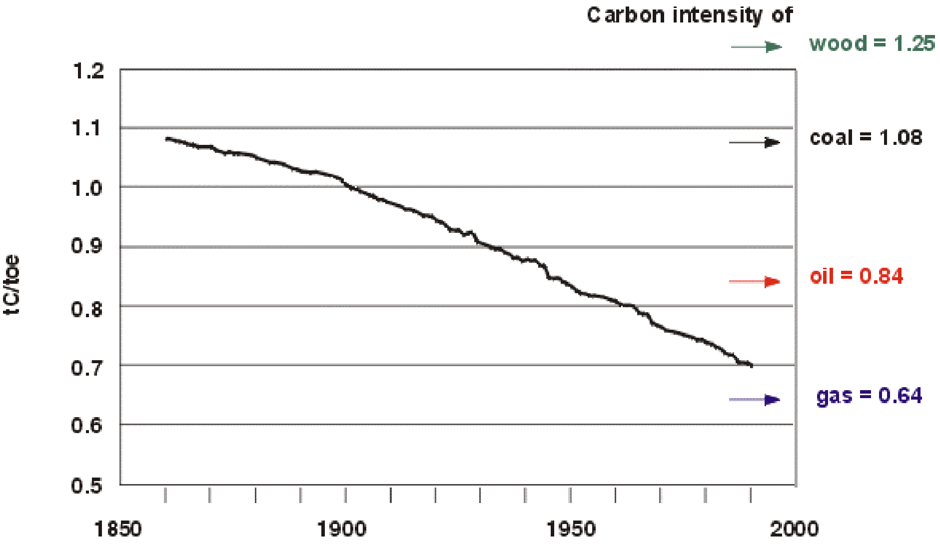


Figure 6: Global decarbonization of energy, historical development from 1860 to 1990, as a ratio of carbon to primary energy (tC/MJ). Source: Nakićenović, 1996.

Energy Intensity

The historical rate of decrease in energy intensity per unit of value appears to have averaged about one percent per year since the mid-19th century and about two percent and more per year in some countries over shorter periods of time (e.g., since the 1970s). The overall tendency is toward lower energy intensities, although paths of energy development in different countries are different and have varied enormously and rather consistently over long periods as illustrated in Figure 7. In some of the rapidly growing countries, commercial energy intensity is still increasing. Because commercial energy replaces traditional energy forms not sold in the markets, total energy intensity may diminishe while commercial energy intensity increases. For example, the present energy intensity of India and its improvement rates are similar to those of the US a century ago.

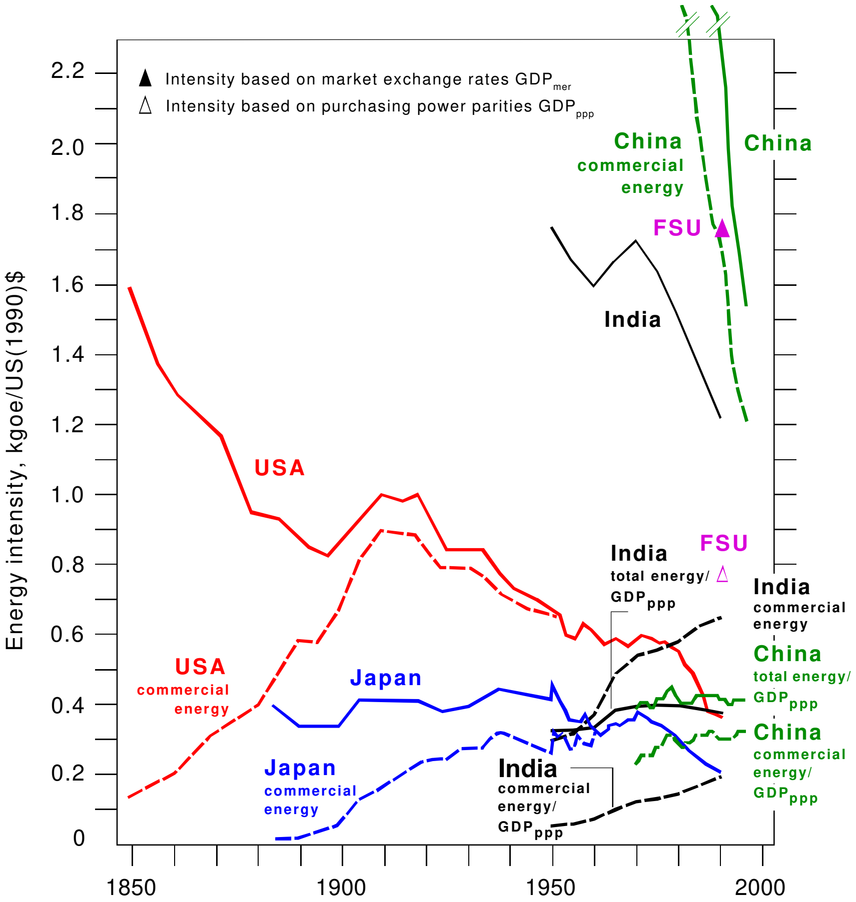


Figure 7: Energy intensity reduction in a number of countries, historical development from 1850 to 1990, as a ratio of primary energy to gross domestic product (MJ/US$). Source: Nakićenović *et al.*, 1998a.

Combining the two factors (carbon intensity of energy and energy intensity of value added) into carbon intensity of value added, reveals large differences in the development paths and structures of energy systems among countries. At the global level, the average annual reduction rate of carbon intensity per unit of value or decarbonization is about 1.3 percent per year since the mid-1800s.

The actual forms of final energy demanded and the structure of energy services matter greatly in the historical drive toward decarbonization. Because electricity and heat contain no carbon, the carbon intensity of final energy is generally lower than the carbon intensity of primary energy. In addition, its rate of decrease exceeds that of primary energy because of the increasing share of natural gas and carbon-free carriers, in the final energy mix. At the level of final energy, decarbonization is a durable, pervasive phenomenon. The likely explanation is a congruence of consumer behavior and preferences as expressed in the structure of final energy use over a wide range of incomes and development levels.

The Historical Energy Evolution

Decarbonization of energy delivered to end use is driven by the increasing need for affordable, clean, flexible and convenient energy forms. Historically this resulted in continuously increasing shares of electricity and hydrogen-rich energy carriers in final energy. This development is likely to continue in the future (Nakićenović, 1996). Thus, the question is whether the drive toward electricity and hydrogen-rich energy can be reconciled with the relatively slow and sometimes, in some places, even opposing changes in the structure of energy systems and the primary energy supply. The historical replacement of coal by oil, and later by natural gas, at the global level indicates the future possibilities. The well-documented evolutionary substitution of primary energy suggests that natural gas and later carbon-free energy forms will become the leading sources of primary energy globally during the 21st century (Ausubel, *et al.,* 1988).

The competitive struggle among the five main sources of primary energy — wood, coal, oil, gas and carbon-free sources (nuclear and renewables) — has proven to be a dynamic and regular process that can be described by relatively simple rules. Figure 8 reveals the dominance of coal as the major energy source between the 1880s and the 1960s after a long period during which (fuel) wood and other traditional energy sources provided for most of the energy needs. The mature coal economy meshed with the massive expansion of railroads and steamships, the growth of steel-making and the electrification of production. During the 1960s, oil assumed a dominant role in conjunction with the development of automotive transport, the petrochemical industry, and many end-use markets for oil products such as the heating oil.

Assuming the same dynamics of primary energy substitution as in the past, an explorative view into the future projects natural gas to be the dominant source of energy during much of the 21st century, although oil should maintain the second largest share

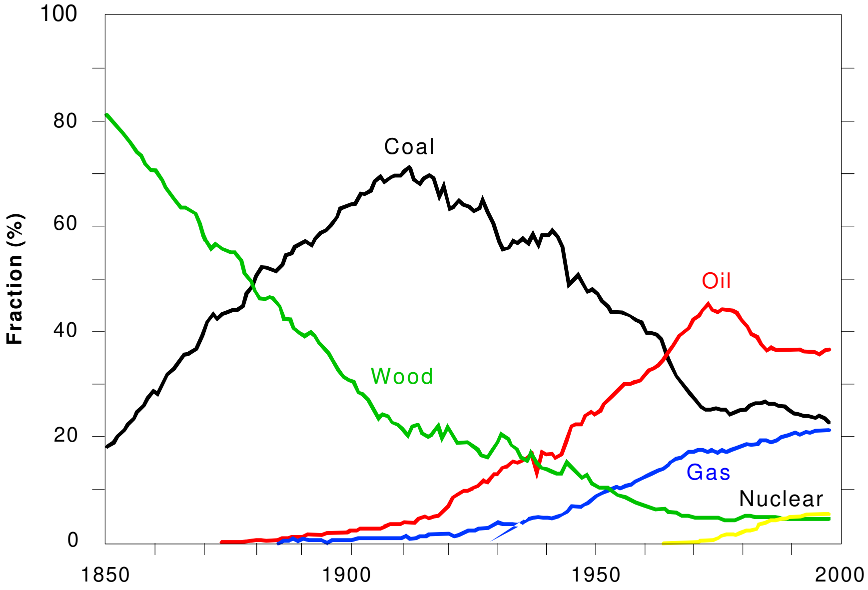


Figure 8: Global primary energy substitution, historical development from 1860 to 1998, in fractional market shares (f). Source: Nakićenović *et al.*, 1998a and Grübler, 1998.

through the 2030s. The unfolding of primary energy substitution in this scenario implies a gradual continuation of energy decarbonization globally (Marchetti, 1985). If natural gas does indeed become the dominant source of energy, this ratio can be expected to approach the level of four hydrogen atoms to one carbon. Improvement beyond this level would have to be achieved by the introduction of carbon-free energy sources, by carbon sequestration from fossil energy and by the sustainable use of biomass.

The Methane Age

A methane economy offers a bridge to the carbon-free energy future consistent with both the dynamics of primary energy substitution and the steadily decreasing carbon intensity of final energy. As carbon-free energy sources start to supplement natural gas in the global energy supply and the role of coal and oil declines, new energy conversion systems would be required to provide gaseous and liquid carbon-free carriers of energy in addition to electricity. The ideal candidate is hydrogen, used as a gas or liquid. Hydrogen and electricity could carry virtually pollution-free, greenhouse-gas-free and environmentally benign energy to end users.

To the extent that both hydrogen and electricity might be produced from methane, the carbon separated as a by-product could be sequestered and used in enhanced recovery of natural gas and stored in subterranean aquifers or in deep ocean. As the methane contribution to global energy supply reaches its limit and subsequently declines toward the end of the 21st century, carbon-free sources of energy would eventually take over, eliminating the need for carbon handling and storage. This would conclude the global energy transition toward decarbonization and the resulting major transformation of the energy system. The emergent near zero-emissions system could cleanly accommodate the foreseeable levels of population and economic activity. This future vision poses formidable challenges, especially for the natural gas industry. It is contingent on the development and successful market deployment of a whole cluster of new methane technologies and changes in the whole energy system and beyond.

In fact, an energy system of the distant future that relies on electricity and hydrogen as the complementary energy carriers would also advance dematerialization. Hydrogen has the lowest mass of all atoms, and its use would radically reduce the total mass flow associated with energy activities and the resulting emissions. Electricity is free of material emissions. The only product of appropriate hydrogen combustion is water. Thus, decarbonization not only contributes to dematerialization but is also consistent with the emergence of new technologies that hold the promise of high flexibility, productivity, affordability and environmental compatibility. Weighty carbon vented to the atmosphere after combustion is a poor match for the evolving final energy demands of modern societies. Fortunately, decarbonization has asserted itself already as a widespread, long-term development driven by deepening and strengthening forces (Nakićenović, 1996). Decarbonization is a proxy indicator for the fundamental transformation of the energy systems that may take a century before being completed. It provides a prospective look into the future.

Global Energy Perspectives

Scenarios are appropriate tools for a more detailed assessment of future energy perspectives and the development of the underlying driving forces. Through developing scenarios, future determinants of energy requirements can be analyzed and matched to supply availability, financing requirements, environmental consequences, and other salient constraints and driving forces.

Important driving forces that influence energy futures in scenarios include population growth, economic development, technological change, the structure of demand for energy services and the structure of the energy system that provides those services. Energy intensity of economic activities (measured as energy consumption divided by the gross domestic product, GDP) is a good indicator for the relationship between energy requirements and economic development and the carbon intensity of energy is a good indicator for transformations in the energy system from more to less intensive energy sources.

Historically, global economic product (or gross world product, GWP) expanded at about three percent per year while primary energy consumption increased at about two percent per year. As mentioned in the previous section, the resulting energy intensity of GWP improved at an average rate of about one percent per year. As in the past, the future relationship between economic and energy growth will also depend, *inter alia,* on the rates of technological and structural change in the energy system. Therefore, assumptions about the future efficiencies of energy technologies and their environmental impacts have a central role in energy and economic scenarios and projections.

Morita and Lee (1998) have developed a unique database of energy scenarios and projections from all the available literature. It includes about 500 different scenarios. The following summarizes some of their results for economic and primary energy development in the world (see Nakićenović *et al.*, 1998b and 2000a).

Figure 9 shows the distribution of global economic scenarios from 1990 to 2100, all normalized to index one for the base year 1990 (1990=1). The range is large, indicating the inherent uncertainty in projecting future economic growth rates. The further one looks into the future, the higher the uncertainty. By 2100, the range is between three and more than 20 times the 1990 level. For 1990, the global economic product is estimated at more than US$20 trillion (1000 billion). Consequently, the scenarios give a range of about $60 to US$700 trillion with a median of US$240 trillion. These figures translate into an annual growth rate variation of between 1.1 to 3.2 percent, with a median growth rate of 2.1 percent. Thus, future economic growth rates are generally assumed to be lower than historical experience.

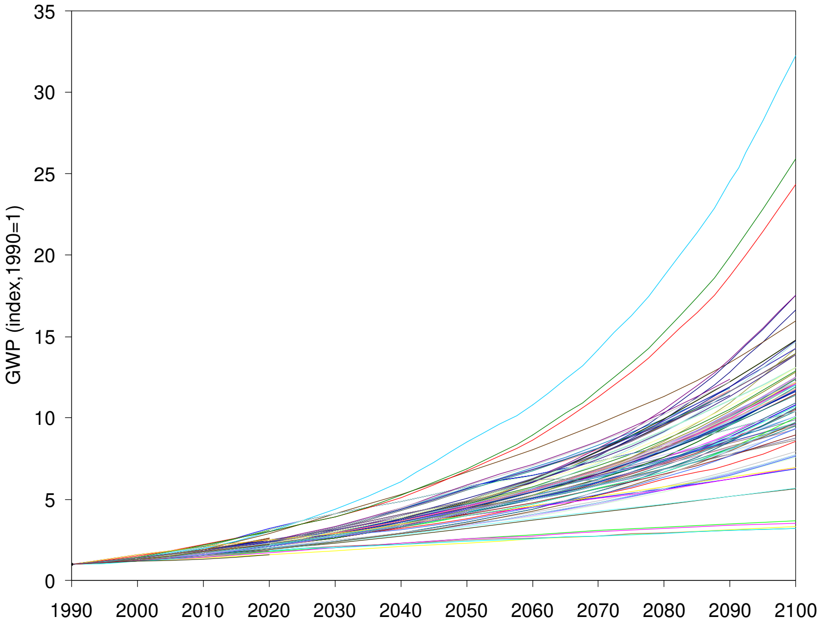


Figure 9: Global scenarios of economic development, 1990 to 2100, normalized to index one (1990=1) for the base year 1990. Source: Nakićenović *et al.*, 1998b and Morita and Lee, 1998.

Figure 10 shows the corresponding global primary energy consumption from the same database. Scenarios are compared to the base year index 100 (1990=1). The range of primary energy is indeed large, from a decline in the lowest scenario to a ten-fold increase in the case of the highest scenarios. In absolute terms, the primary energy requirements are expected to range from a decline to 7 Gtoe (280 EJ) in 2100, compared to 9 Gtoe (370 EJ) in 1990, to almost 80 Gtoe (3200 EJ) in 2100. The highest energy requirements correspond to an annual growth rate of two percent, exactly in line with historical experience. Further, and also in line with historical experience, many scenarios foresee a growing demand for hydrocarbon energy sources even if the relative shares compared to alternative energy sources might be declining. This again amplifies the need for a continuing improvement in energy efficiencies.

Taken together, energy requirements are envisaged to increase at lower rates than economic growth. This means that energy intensity is presumed to decline across all scenarios. By 2100, it falls to between 80 and less than 20 percent of the 1990 levels. This translates into annual declines of between 0.2 and more than 1.5 percent, a median of about one percent per year. Thus, future energy intensity improvements are generally also assumed to be in line with historical experience.

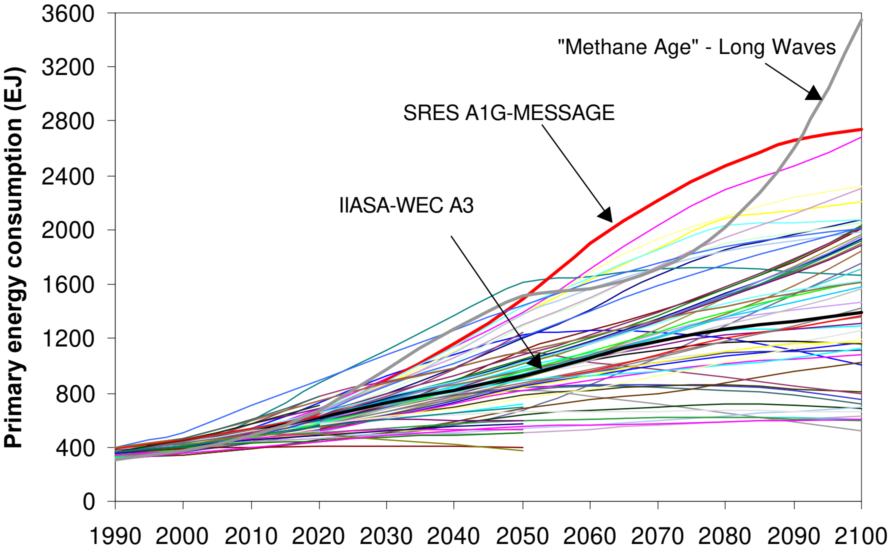


Figure 10: Global scenarios of primary energy consumption, 1990 to 2100, normalized to index one (1990=1) for the base year 1990. Source: Nakićenović *et al.*, 1998b.

Challenging Prospects for Methane

Much of the increase in global primary energy envisaged in the scenarios relies on the substantial and often quite challenging contribution of natural gas. In a number of scenarios, natural gas is expected to approach half of all primary energy reaching up to 30 Gtoe (1300 EJ) per year. This corresponds to more than three times the total current global energy requirements or more than 15 times the current global gas production! This magnitude is difficult to envisage from current perspectives. For example, the present conventional gas reserves would last a mere five years at this voracious consumption level.

Figure 11 shows the absolute use of natural gas across 64 scenarios from the literature (as documented by the scenario database, see Morita and Lee, 1998). Most of the scenarios cluster in the region of up to some 10 Gtoe (400 EJ) by 2100, corresponding to the total global energy consumption at present. A few of the scenarios that extend beyond this range are shown as continuous colored curves. Among the highest natural gas scenarios in the literature are three developed at IIASA. They include a "gas-intensive" high-growth (A1G-MESSAGE) scenario developed for the recent IPCC Special Report on Emissions Scenarios (Nakićenović *et al.,* 2000a and Roehrl and Riahi, 2000), a "clean-fossil" (A3) scenario developed for the joint IIASA-WEC study on

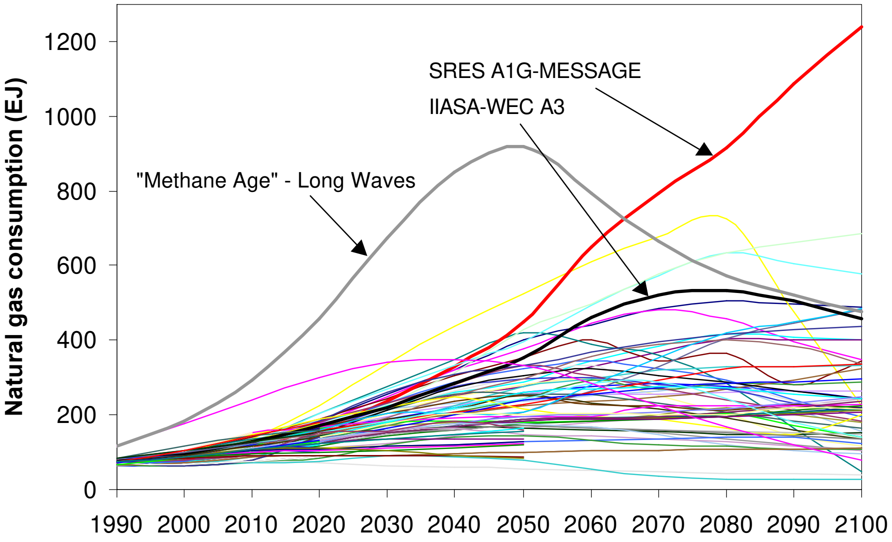


Figure 11: Global scenarios of natural gas consumption, 1990 to 2100, in EJ per year. Data source: http:www-cger.nies.go.jp/cger-e/db/ipcc.html.

Global Energy Perspectives (Nakićenović *et al.,* 1998a and Nakićenović *et al.,* 2000) and a "methane age" scenario that explores a future transition toward natural gas as the dominant source of energy (Ausubel *et al.,* 1988). The three scenarios have little in common. For example, they are based on different projections of future global population growth, economic development and technological change. They are based on different modeling approaches. Jointly, they indicate that different sets of driving forces and methodological approaches can result in scenarios that envisage large future contributions of natural gas to the future global energy supply. This means that the possibility of such developments is relatively robust even against changes in the main scenario assumptions and methods of scenario development.

Figure 12 shows the shares of natural gas in total primary energy across the 64 scenarios from the literature. As mentioned, natural gas approaches half of total energy after the 2050s in some scenarios. This development is especially pronounced in the three scenarios developed at IIASA (A1G-MESSAGE, IIASA-WEC A3, and the "methane age") during the post-2050 period. Natural gas shares exceed 45 percent for periods lasting more than a decade. In addition, there are a few other scenarios that substantially exceed the three scenarios developed at IIASA during the pre-2050 period. Some of them envisage natural gas shares of more than 40 percent already within the next 20 years. All told, recent global energy scenarios include many that are exceedingly "bullish" about the future role of natural gas in the global energy supply. This is a major paradigm shift compared to older studies that considered natural gas to be a "premium" and very scarce source of energy best reserved for most important uses.

Clearly, there are many scenarios in the literature that do not foresee a crucial role for natural gas in global energy. These more traditional scenarios anticipate that the more limited and scarce gas reserves best be preserved rather than consumed. In fact, this is the case in the majority of older scenarios in the literature. Often, the future role of natural gas is directly limited through very limited reserves of conventional natural gas. This is in fact the crucial difference compared to the three scenarios developed at IIASA that lead to a future reliance on natural gas. Recent assessments of energy resources convincingly indicate that hydrocarbon deposits are much more abundant and pervasive than previously believed. This is also the case for natural gas which is usually the fuel of choice when available.

Thus, the question of how long this envisaged methane age in the scenarios can last is really an issue of how abundant hydrocarbon and, in particular, methane resources are. Cumulative natural gas consumption across the scenarios can offer an indirect indication of how large the resources are assumed to be and, in comparison, how long the currently estimated reserves and resources might last without new discoveries. The cumulative natural gas consumption from 1990 to 2100 ranges between 5.7 and 62.3 ZJ (128 to 1402 Gtoe) across the 64 scenarios in the literature shown in Figure 12. The lower quantity is consistent with the known reserves of conventional gas while the higher one implies vigorous development of unconventional gas. The highest cumulative natural gas needs are from the "methane age" scenario (Ausubel *et al.,* 1998) while the gas-intensive IIASA-WEC A3 scenario (Nakićenović *et al*., 1998a) requires about half that amount (35.5 ZJ or 799 Gtoe); both scenarios are shown in Figure 12. The global cumulative natural gas consumption from 1860 to 1990 of some 1.6 ZJ (36 Gtoe) appears miniscule in comparison. This illustrates some of the daunting challenges that have to be mastered in the future before natural gas could become the dominant energy source in the world.

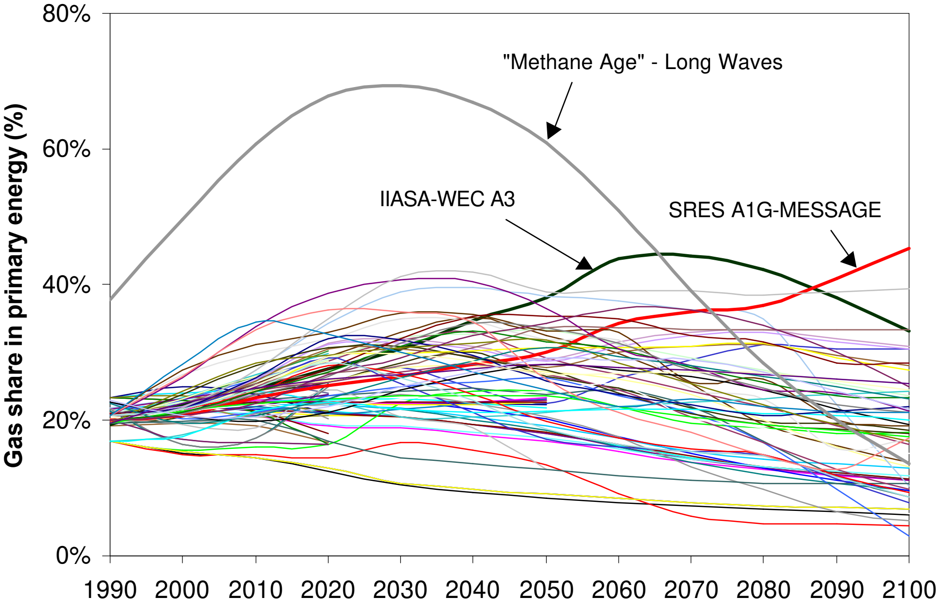


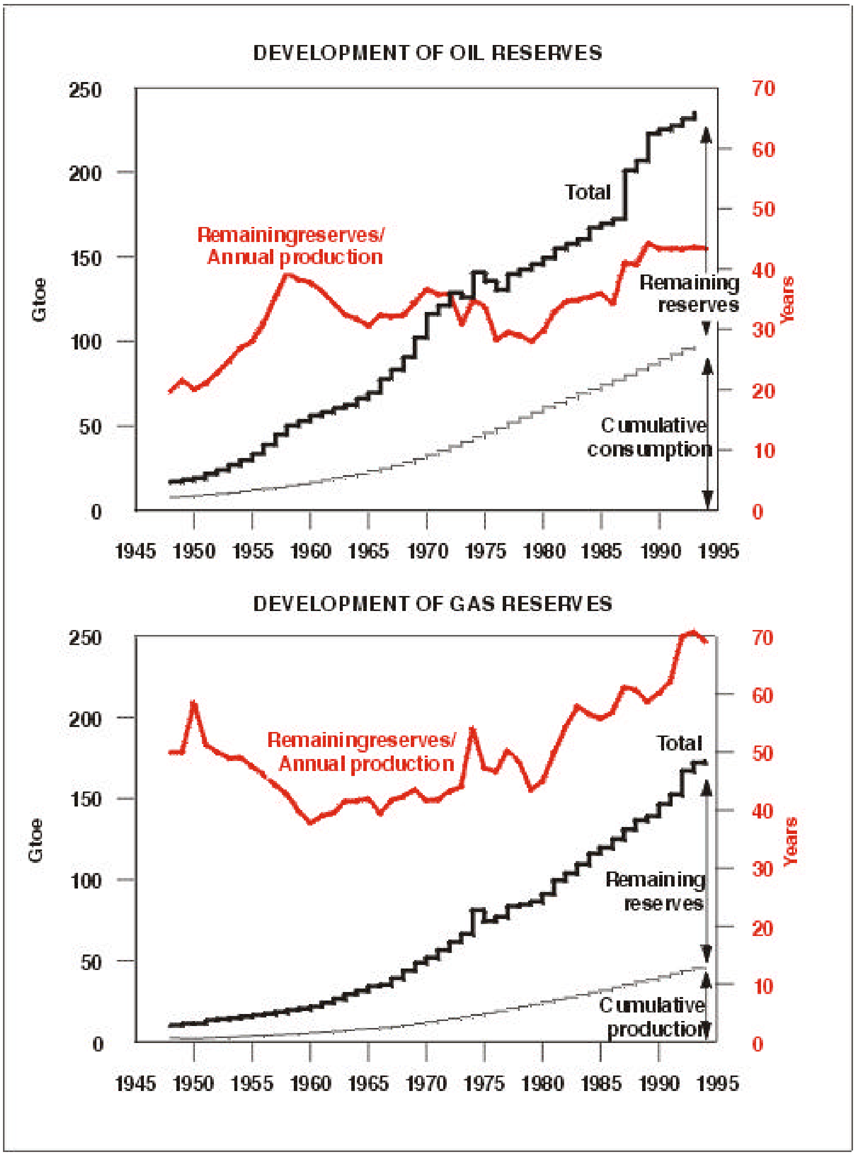
Figure 12: Global scenarios of natural gas consumption, 1990 to 2100, relative shares in percent. Data source: http:www-cger.nies.go.jp/cger-e/db/ipcc.html.

From Hydrocarbon Resources to Reserves

The availability and environmental impacts of energy are to a large degree a function of energy technologies. Historically, this has certainly been the case with hydrocarbon sources of energy. Improvement in energy technologies has reduced the adverse environmental impacts of energy at all scales and, at the same time, has also increased the estimates and availability of energy sources. In a way, the quantity of hydrocarbon energy thought to be in the Earth's crust can be considered as a growing resource endowment. However, resources are not an end in themselves and their attractiveness must be seen in context with the energy service needs of our societies, the technologies which convert different resources into energy services, and the economics associated with their use. As technologies improve, it becomes possible to economically assess and extract deeper, lower quality and more remote deposits. In fact, the growth of oil and gas reserves outpaced the growth in oil and gas production. Figure 13 shows the history of oil and gas cumulative production, reserves and increases in reserve-to-production ratios over the last four decades (Nakićenović *et al.*, 1998a). Reserve additions have shifted to inherently more challenging and potentially more costly frontier locations, with technological progress outbalancing potentially diminishing returns.

However, with reserve-to-production ratios above 40 years, there is little economic incentive for the private sector to vigorously explore and develop more reserves (Nakićenović *et al.*, 1998a). Generally, the lifetime of capital for energy extraction and conversion is shorter than four decades. Thus, it is now often argued in the literature that the magnitude of ultimately recoverable hydrocarbon deposits is not fixed or limited and that the reserve base will expand in the future with growing oil and gas production (Rogner, 1996; Adelman and Lynch, 1997). The situation with coal is even more extreme. Coal is known to be abundant so that extraction is more a question of economic, environmental and other considerations rather than one of availability of appropriate deposits.

Hydrocarbon energy resources can be classified according to a two-dimensional matrix originally proposed by McKelvey (1972). One axis of the matrix represents decreasing geological certainty of resources occurrence. The other represents decreasing economic recoverability. Both dimensions are a function of technologies. Geological certainty depends both on advances in the science of geology and on the prospection and extraction technologies, while the economics of recoverability depend on energy prices and extraction technologies. Thus, the concept of energy resources is dynamic with global resources growing faster than energy consumption. All types and forms of hydrocarbon deposits are collectively called "occurrences." What is considered to be a hydrocarbon occurrence has changed drastically during the last three decades since the so-called energy crisis. For example, gas hydrates were known to exist then, but they


DEVELOPMENT OF OIL RESERVES

DEVELOPMENT OF GAS RESERVES

Figure 13: Technically and economically recoverable reserves and cumulative production of conventional oil, top figure, and conventional natural gas, bottom figure. Source: Nakićenović *et al*., 1998a.

were not considered as a potential source of energy. Today, they are being investigated as the potentially largest speculative source of natural gas.

Table 1 summarizes recent estimates of hydrocarbon energy occurrences in the world from a number of literature sources and gives the maximum occurrences of oil, natural gas and coal derived from the literature (Nakićenović *et al.*, 1996; Nakićenović *et al.*, 1998a, WEC, 1993, Masters *et al.*, 1994; Rogner, 1996; and Rogner *et al.*, 2000). The estimates were chosen so as to correspond to the highest plausible values from the literature. They indicate that severe resource constraints can be avoided even over time scales of centuries provided that the appropriate technological development actually takes place. This is especially the case as far as oil and gas occurrences are concerned. Given current oil and gas reserve-to-production ratios of some four decades, it is obvious that the currently estimated reserves will be depleted long before the energy era of hydrocarbons is likely to come to an end. Thus, without the appropriate technological development that leads to continuous transfer and reclassification of some resources into reserves, the availability of hydrocarbon energy sources might indeed become limited during 21st century.

Table 1: Global hydrocarbon reserves, resources, and occurrences, in ZJ (10^{21}J). Data sources: Nakićenović *et al.*, 1996; Nakićenović *et al.*, 1998a, WEC, 1993, Masters *et al.*, 1994; and Rogner, 1996.

	Coal	Oil	Gas	Total
1860-1998	6.6	4.5	1.7	12.8
1998	0.09	0.14	0.08	0.31
Reserves	45	12	9	66
Resources	108	17	> 15	> 140
Additional Occurrences	> 130	> 60	> 810	> 1000

Table 1 gives hydrocarbon energy occurrences divided into reserves, resources and the resource base. Reserves are those occurrences that are known and are recoverable with present technologies at prevailing market conditions. Resources are occurrences in addition to reserves, with less certain geological assurance, or lacking present economic feasibility, or both. Changing market conditions, innovation diffusion, and advances in geosciences can transform resources into reserves. Thus, the growth of reserves can occur even without new resource discoveries. The resource base is the sum of reserves and resources. It includes all potentially recoverable coal, conventional oil and natural gas, unconventional oil resources (such as gas in shale, tar sands, and heavy crude), and unconventional natural gas resources (such as gas in Devonian shale, tight sand formations, geopressured aquifers, and coal seams). Additional occurrences are all other hydrocarbon deposits that are known to exist but are associated with great uncertainty about their extent, technology and economics of recovery. Methane hydrates are a good example of a clean and potentially enormous energy resource. Recent estimates indicate that there might be three times more natural gas deposited in hydrates than in all other hydrocarbon occurrences.

Driven by economics, technological and scientific advances, and policy decisions, the hydrocarbon resource base has expanded over time, and reserves have been continuously replenished from resources and from new discoveries (Masters *et al.*, 1994; Nakićenović *et al.*, 1998a; Rogner, 1996; and Adelman and Lynch, 1997). Thus, it can be expected that the hydrocarbon resource base is likely to expand and exceed the current estimates shown in Table 1. Deposits currently classified as occurrences will enter the resource base and eventually become reserves. The argument then becomes more one of cost and development of extraction and treatment technologies rather than of ultimately available reserves (Gregory and Rogner, 1998).

Currently identified global hydrocarbon energy reserves are estimated at more than 66 ZJ (66,000 EJ or about 1,600 Gtoe). This quantity is theoretically large enough to last more than 200 years at the current level of global hydrocarbon energy consumption (310 EJ or 8.5 Gtoe in 1998), or is five times larger than the total cumulative hydrocarbon extraction since 1860 (Nakićenović *et al.*, 1996). Coal accounts for more than half of all hydrocarbon reserves. Nevertheless, even oil and gas reserves would last for about 120 years at current global consumption levels.

Current estimates of hydrocarbon resources and additional occurrences are much larger but more uncertain than reserves. The global resource base (reserves and resources) is estimated at some 200 ZJ (5,000 Gtoe), with additional occurrences of more than 700 ZJ (25,000 Gtoe), mostly in the form of gas hydrates. Thus, hydrocarbon sources of energy are abundantly available in the world and the known deposits are likely to last more than a century, and with technological and scientific progress in energy extraction, many centuries.

What is limited is conventional oil, currently the fuel of choice for most end uses, especially transportation. Much of the abundant occurrences of hydrocarbons consist of coal and unconventional oil and gas. Use of these sources of energy is associated with adverse environmental impacts. As more difficult, lower quality and more remote deposits are exploited, it can be expected that environmental impacts will increase unless vigorous mitigation measures are enacted. In other words, what is limited are “clean and easy” hydrocarbon deposits. Thus, improvements in efficiency and environmental compatibility of energy technologies are important prerequisites for utilizing more difficult hydrocarbon deposits.

Deposits of conventional oil and, consequently, also oil production are unevenly distributed around the world. The world’s reserves continue to be dominated by the Middle East that holds over 65 percent of the total. In fact, Masters *et al.* (1994) argue that certain areas of the world are more likely to contain oil resources than others due to specific geological conditions. This hypothesis is strengthened through the observation that a growth in reserves has been achieved in many parts of the world through a revision of the estimates based on changed economics and extraction technologies rather than on new discoveries (Smith and Robinson, 1997). Earlier discoveries previously regarded as uneconomic can now be developed profitably and recoverable reserves estimates can be increased in fields under development or construction.

Smith and Robinson (1997) give examples of technological progress that has led to these improvements. For instance, three-dimensional (3D) seismics prospection methods have led to more discoveries and guided improved recovery by facilitating infill drilling. New drilling techniques such as extended reach through horizontal drilling has allowed adjacent reservoirs up to ten kilometers away to be reached more economically from the drilling site. Horizontal drilling has allowed more difficult reservoirs to be exploited, such as those with thin or fractured "pay zones," low energy, high viscosity fluids, or generally poor flow characteristics, and for recovery rates to be higher (Gregory and Rogner, 1998). Smith and Robinson (1997) also estimate that the replication of the experience of the Northwest European Continental Shelf to the whole world translates into reserves increment due to drilling advances of as much as 2 ZJ (350 billion barrels or 48 Gtoe). Thus, technological advance is of critical importance for both expanding the global reserves of conventional oil and making more abundant unconventional sources of oil more accessible for economic extraction.

The situation with natural gas is slightly different. Traditionally, gas was less valuable than oil so that most gas discoveries were in fact "accidental" results of unsuccessful oil exploration efforts. As technologies improve so that deeper drilling becomes more economical, the chances of gas discoveries increase. In summary, the potential for discoveries of major quantities of gas in the 21st century is high (Gregory and Rogner, 1998). Table 1 gives the global conventional and unconventional gas reserves of some 9 ZJ (240 Tm^3) and resources with more than 15 ZJ (400 Tm^3). Unconventional sources such as hydrates are known to be vast with some 810 ZJ (22,000 Tm^3). Thus, one of the key questions is whether the new and improved technologies will transfer some of the resources into reserves. Today, most natural gas reserves are limited to two world regions: the territory of the former Soviet Union (Siberia and the Caspian) and the Middle East. Together they hold more than 70 percent of the world's resources (BP, 1997). Table 2 illustrates this uneven distribution of natural gas reserves throughout the world.

The nature and global distribution of coal are different from oil and gas. In terms of conventional reserves, coal reserves are clearly the world's largest hydrocarbon energy sources. In contrast to oil and gas, the estimates of coal reserves have been relatively stable at more than one trillion tons ever since the first global inventory of coal resources was presented at the International Geological Congress in 1913 (Rogner, 1996). This is in agreement with the current estimates of about 45 ZJ (1,100 Gtoe, see Table 1). The coal resource base is so large that it represents two-thirds of the global hydrocarbon resource base. Coal deposits, unlike those of oil and gas, are more evenly distributed around the world.

Table 2: Estimates of regional natural gas reserves. Data sources: WEC, 1998; BP, 1998; and IGU, 1997; Rogner *et al.*, 2000.

Region	WEC 98 Proved recoverable reserves		WEC 98 Total reserves recoverable		IGU-97 Proven additional Reserves		BP 98 Proved reserves		Enhanced gas recovery (EGR)	
	EJ	Tm^3	EJ	Tm^3	EJ	Tm^3	EJ	Tm^3	EJ	Tm^3
North America	252	6.8	389	10.5			244	6.6	884	23.9
Latin America & Caribbean	303	8.2	426	11.5			300	8.1	306	8.3
Western Europe	181	4.9	300	8.1			189	5.1	306	8.3
Central & Eastern Europe	26	0.7	26	0.7			19	0.5	45	1.2
Former Soviet Union	2,087	56.4	2,583	69.8			2,098	56.7	1,923	52.0
Middle East & North Africa	2,076	56.1	2,250	60.8			2,024	54.7	1,421	38.4
Sub-Saharan Africa	155	4.2	155	4.2			152	4.1	93	2.5
Pacific Asia	207	5.6	207	5.6			192	5.2	158	4.3
South Asia	63	1.7	63	1.7			52	1.4	50	1.4
Centrally Planned Asia	48	1.3	48	1.3			74	2	41	1.1
Pacific OECD	56	1.5	89	2.4			22	0.6	62	1.7
Total	5,450	147.3	6,534	176.6	14,963	404.4	5,358	144.8	5,290	143.0

Sources: WEC, 1998; BP, 1998; and IGU, 1997; Rogner *et al.*, 2000.

One of the important difficulties in translating estimates of coal reserves and resources into energy terms is that the heating values of different deposits vary over a wide range. The coal characteristics specific to one location cannot be easily generalized. Yet, the reserves are usually reported in terms of physical quantities. It is quite possible that a large portion of deposits currently classified as reserves are uneconomic. Taking into account the quality and location of some reserves, Shell (1996) argues that it is very hard to make a case for competitively producing and marketing more than 600 to 800 billion tons. Thus, further consideration must be given to both the costs and environmental impacts of coal production.The future improvement of coal extraction technologies toward lower material use and lower environmental impacts will play a key role in determining whether coal can be the fuel of choice, especially in the developing countries rich in coal deposits. For example, extraction of methane from coal deposits instead of coal would reduce both material requirements and overall environmental impacts. This is another abundant category of "unconventional" gas to be exploited in the future.

Table 3: Carbon content of global energy reserves, resources, and occurrences, in GtC.

	Coal	Oil	Gas	Total
1860-1998	139	96	35	270
1998	2	3	1	6
Reserves	1170	240	140	1550
Resources	2800	340	> 220	> 3360
Additional Occurrences	> 3000	> 1000	> 10000	> 14000

An important conclusion is that estimated hydrocarbon energy occurrences is indeed very large. What is limited is the availability of conventional oil and gas. What is certainly limited is the availability of clean energy and environmentally benign energy. Table 3 illustrates this point clearly. It expresses the hydrocarbon energy resource base and additional occurrences from Table 1 in terms of carbon content rather than in terms of energy. The total "hydrocarbon endowment" available to future generations corresponds to more than 14,000 Giga or billion tons of elemental carbon (GtC). Hydrocarbon energy reserves correspond to 1,550 GtC, nearly twice the current carbon content of the Earth's atmosphere (about 760 GtC, corresponding to an atmospheric concentration of 360 parts per million). The resource base, with almost 5,000 GtC, is about six times as large as the current atmospheric carbon content. This illustrates quite clearly that the carbon endowment is not likely to be combusted but that a large part of estimated deposits will remain undisturbed because the assimilative capacity of the atmosphere and biosphere would be exceeded long before the ultimate hydrocarbon resource limits are encountered.

From Certain to Speculative Methane Deposits

There is less controversy surrounding estimates of ultimately recoverable reserves of gas compared with oil. Proven reserves are high both in relation to current production (BP, 1996) and to cumulative production to date. However, Masters *et al.* (1994), Ivanhoe and Leckie (1993) and Gregory and Rogner (1998) note that gas discoveries need to be matched to an infrastructure for gas supply and consumption, which is currently lacking in many parts of the world. In particular, the development of new natural gas fields requires large infrastructure investments in transmission and distribution systems. As a consequence, gas discoveries, especially in developing countries, are often not even reported. But this does not imply a lack of gas occurrence**.** In summary, the potential for discoveries of major quantities of gas in the 21st century remains high (Rogner *et al.*, 2000).

All this has limited exploration and the potential for discoveries of major quantities of gas in the 21st century is high. Estimates of gas reserves and resources are being revised continuously. The most up to date information is represented by the figures of the International Gas Union (IGU, 1997) giving conventional gas reserves of 5 ZJ plus 10 ZJ additional reserves, including gas yet to be discovered. On the basis that some of the IGU regional estimates of reserves are extremely conservative, Gregory and Rogner (1998) suggest an optimistic estimate of ultimately recoverable reserves of 28 ZJ (5 ZJ reserves plus 23 ZJ additional reserves, including quantities to be discovered) based on the same ratio of optimistic to pessimistic reserves used by Masters *et al.* (1994).

In addition to conventional reserves, the literature indicates very substantial amounts of unconventional gas occurrences. BGR (1995) defines unconventional gas as gas derived from reservoirs not exploitable by conventional recovery techniques, including the following sources: coal-bed methane; tight formation gas; geopressured gas (from aquifers); and gas hydrates (clathrates). Rogner (1996 and 1997) estimated resources in place for coal bed methane of 10 ZJ, gas from fractured shale of 17 ZJ, tight formation gas of 7 ZJ, gas remaining *in situ* after production of 5 ZJ, and methane hydrates, also known as clathrates, at some 980 ZJ. The magnitude of these estimates is also confirmed in two consecutive IPCC assessments of energy resources (Watson *et al.*, 1996, Nakićenović *et al.*, 2000a), that classifies 7 ZJ unconventional gas as current reserves, and additional 2 and 18 ZJ as recoverable with current or foreseeable improvements in technologies respectively and hydrate occurrences at some 800 ZJ. Thus, the largest occurrence of all hydrocarbon energy forms (even exceeding coal) is estimated to be in the form of methane hydrates. Also called clathrates, methane hydrates represent gas that is locked in frozen ice-like crystals that probably cover a significant proportion of the ocean floor and have been found in numerous locations in continental permafrost areas. It is plausible that technologies for recovering these resources economically could be developed in the future, in which case gas resource availability would increase enormously (MacDonald, 1990a; MacDonald, 1990b).

Conventional Gas

The most recent estimates of conventional gas reserves are given by the WEC (1998) for the end of 1996 and BP (1998) for the end of 1997. WEC gives total reserves as 176.6 Tm^3 (6,534 EJ) at the end of 1996, of which 147.3 Tm^3 (5,302 EJ) were proven recoverable reserves, the remaining being additional recoverable reserves. The International Gas Union (IGU, 1997) reports reserves as high as 257 Tm^3 (14,963 EJ). Generally, reserves have increased from survey to survey, a result of the dramatic changes in the economics of gas exploration and recovery. Reservoirs are being added in areas previously thought to have been exhausted, and new reservoirs that previously were overlooked or ignored are now being developed. Over the last decade, reserve additions averaged 3.7 Tm^3 (134 EJ) per year, substantially higher than the 1997 production of 2.2 Tm^3. Ivanhoe and Leckie (1993) note that fewer gas than oil fields are reported in developing regions of the world and that this is probably due to the current lower value of gas rather than to the existence of fewer gas fields. In summary, the potential for discoveries of major quantities of gas in the 21st century is high. A regional breakdown of world gas reserves is given in Table 2 (Rogner *et al.*, 2000).

Enhanced gas recovery utilizing advanced recovery methods, notably hydraulic fracturing aimed at improving the permeability of the reservoir rock, can substantially increase natural gas recovery in abandoned fields and newly developed reservoirs. Another more innovative technique, horizontal air drilling, can also achieve increased gas recovery in depleted gas zones (Elrod, 1997).

Estimates of potential reserves of natural gas resulting from enhanced gas recovery are based on the assumption of a historical average gas recovery rate of 50 percent and an enhanced recovery of 30 percent yielding a total recovery factor of 80 percent. Similar assumptions are used by Schollenberger (1998) in an assessment of possible future reserve development through the year 2100. Global cumulative natural gas production through 1998 comes to about 62 Tm^3 (2,276 EJ). Applying an average recovery factor of 50 percent leads to an original amount in place of 124 Tm^3 (4,587 EJ) enhanced recovery then enlarge gas reserves by some 37 Tm^3 (1,369 EJ) based on an enhanced recovery factor of 30 percent. Likewise, enhanced-recovery reserves from future production are estimated at 106 Tm^3 (3,921 EJ) using WEC (1998) total recoverable reserves of 177 Tm^3 (6,534 EJ; see also Table 2).

Thus, total potential natural gas reserves available from enhanced recovery methods are estimated at 143 Tm^3 (5,290 EJ), an amount only slightly lower than proven natural gas reserves and almost identical to the potential crude oil reserves expected from EOR (Rogner *et al.*, 2000).

Coalbed Methane

Mixtures of hydrocarbon gases occur naturally in high-rank coal seams. They consist mostly of methane, often more than 90 percent. Methane from coal beds can migrate into the surrounding rock strata. Methane contents found in coal seams can range from traces to 25 m^3/t of coal (1 GJ/t; Davidson, 1995). The regional resources of coalbed methane are genetically associated with the geographical distribution of bituminous coal and anthracite deposits. The former Soviet Union accounts for nearly half of recoverable resources, while about 20 percent are located in Centrally Planned Asia (China) and 15 percent in North America (Rogner *et al.*, 2000).

Coalbed methane (CBM) can be a by-product of underground coal mining or be produced exclusively to recover methane. In fact, methane represents an explosion hazard in underground mining operations and traditionally has been vented with mine fresh air circulation for safety reasons. Since the 1970s methane capture from underground mining has increasingly been used to supplement local gas supplies. Capture and use can also have a significant GHG mitigation effect as it avoids the release of methane, in itself a potent GHG, and it may replace fuels with a higher carbon content. With regard to long-term and stable methane supplies from coal beds, dedicated drilling for gas in coal beds is more important than the methane from active underground coal mines.

At present commercial coal bed methane production occurs only in the US and contributes about five percent to natural gas production (BGR, 1998). Pilot projects are under way in a number of other countries, including China, India, Australia, Great Britain, Poland, Russia and Ukraine (Rogner *et al.*, 2000).

Estimates of in-place methane resources range from a low of 85 Tm^3 (3 ZJ) to a high of 262 Tm^3 (10 ZJ) (BGR, 1998; BGR; 1995; Rice *at al.*, 1993). The BGR (1995) and Rogner *et al.* (2000) estimate is 233 Tm^3 (8.6 ZJ).

Tight Formation Gas

Natural gas can be trapped in low-permeability (“tight”) reservoirs with *in-situ* permeability of less than 0.1 millidarcy (mD), regardless of the type of the reservoir rock (Law and Spencer, 1993). Production of tight gas requires artificial stimulation techniques to improve reservoir permeability, such as massive hydraulic fracturing. An advanced technique is horizontal drilling to develop tight gas formations, frequently in combination with massive hydraulic fracturing. Gas flow rates of two to three-times those of conventional vertical wells can be achieved with these stimulation methods. In recent years about three percent of world natural gas production has come from tight gas reservoirs (Rogner *et al.*, 2000).

Although tight gas reservoirs are known to exist in many regions of the world, to date only the tight gas resources in the US have been assessed. The total potential of tight gas resources from both tight sandstone and Devonian shale reservoirs in the US has been assessed at 13.4 Tm^3 (500 EJ) (BGR, 1995).

BGR (1998) applies these US estimates to extrapolate tight gas resource potential for other world regions and arrives at a global potential of 114 Tm^3 (4.2 ZJ).

Geopressured Aquifer Gas

In many parts of the world natural gas, primarily in the form of methane, is found dissolved in aquifers under normal hydrostatic pressure (Marsden, 1993). This type of unconventional natural gas is also referred to as hydro-pressured gas or brine gas. The amount of natural gas dissolved in underground liquids increases substantially with depth. At depths of 4,000 m an average of 0.5 to 1.5 m^3 of gas is dissolved per m^3 of water in aquifers, while this gas factor increases to between seven and 20 times as much at depths of 7,000 to 8,000 m (BGR, 1995).

Aquifer gas is expected to occur in nearly all sedimentary basins of the world (Marsden, 1993). While no detailed assessment of aquifer gas resources is available, BGR (1998) derives the world potential of aquifer gas from the groundwater volume contained in high-permeability sand stones in the hydrosphere. According to Rogner *et al.* (2000) this approach leads to an estimated range of 2,400 to 30,000 Tm^3 (90 to 1100 ZJ) of geopressured gas in place with a mean estimate of 16,200 Tm^3 (600 ZJ). Clearly, this is quite a speculative estimate.

While these estimates of aquifer gas occurrences are highly speculative, the potential quantities are staggering. Even a future recovery factor of five percent implies a resource volume five times that of the conventional reserves estimates of BP (1996). As regards production experience, brine gas is already produced in small quantities from shallow reservoirs in the US, Italy and Japan. However, in all cases the motivation for brine gas recovery has been the production of trace elements such as iodine rather than the gas itself.

Methane Clathrate Hydrates

Clathrates are ice-like compounds in which various gases are held in crystalline cages formed by water molecules. They form under conditions of high pressure and low temperatures. During the 1940s problems with pipeline transmission of natural gas in cold regions led to widespread recognition that methane hydrates would be stable below ground in regions of permafrost. In these cold regions, drilling operations have to take special precautions to prevent explosive release of methane as the drill penetrates zones of methane hydrates. Methane clathrates or hydrates are widespread in areas of permafrost on and off-shore such as in the polar regions and in sediments on the continental shelf below the ocean floor at shallow depths where conditions are appropriate for their formation (MacDonald, 1990 and 1998; Kvenvolden, 1998). Methane hydrates are an energy source of potentially staggering magnitude compared with other known hydrocarbon deposits. It is thus not surprising that a number of scientific inquiries around the world are evaluating gas hydrates as a potential energy source (IGU, 1997). At the same time, methane hydrates are a factor in climate change. Methane is a potent greenhouse gas which can be released from hydrates by pressure reduction due to giant submarine landslides or by warming of the subsurface sediments (MacDonald, 1998).

At the present time the exact quantities of methane that might be in the form of clathrates are subject to speculation. However, the existence of gas hydrates has been confirmed by direct evidence through sampling and by indirect evidence through geochemical and geophysical investigations. In 1972, the first successful recovery of natural methane hydrate occurred during pressurised coring operations in Prudhoe Bay at depths between 577 and 766m (MacDonald, 1998). Despite the difficulties associated with the recovery of material that rapidly decomposes at low pressures, numerous samples of methane hydrates have been recovered in the course of the scientific program of deep drilling in the ocean. To date, samples have been recovered in 14 areas of the world, while indirect evidence has been found in 30 other areas. Many occurrences of methane hydrates on the continental shelves of all oceans have been inferred based on special geophysical exploration techniques such as bottom-stimulating reflection. At this juncture, resource estimates for gas hydrates are highly uncertain. BGR (1998) reports global clathrate occurrences of more than 9,000 Tm^3 (333 ZJ). Other estimates report clathrates as high as 20,000 Tm^3 (740 ZJ) (MacDonald, 1990a; MacDonald, 1990b; Kvenvolden, 1988; Collet, 1993). Thus, the methane hydrate resource base measured in energy content might be up to five times larger than that of coal. Figure 14 shows the geographical distribution of methane clathrate occurrences.

Figure 14: Map of the geographical distribution of methane clathrate occurrences. Source: Macdonald, 1998 updated from Kvenvolden, 1988.

Methane can be recovered from natural gas hydrates by depressurization or thermal disassociation. How much can be practically recovered at affordable costs is however highly uncertain. Many offshore hydrate occurrences appear to contain free methane as a gas beneath solid hydrate layers. This is because the stability of hydrates depends both on pressure and temperature. Even at high pressures, the reservoir temperature can be too high so that free gas may accumulate and be trapped beneath solid hydrate. An emerging view is that this free gas is easier to recover directly than the gas from solid hydrates (Max *et al.*, 1997). For example, free gas recovery would depressurize the reservoir, which would lead to hydrate melting and thus to free gas replenishment. The process could continue as long as the hydrate layer remains thick enough to cap the free gas below.

The direct recovery of methane from solid hydrate would in any case have a positive energy balance. The energy required to liberate the methane is likely to be 13 to 17 times smaller than the thermal energy contained in the released methane (MacDonald, 1998). However, the economics of methane production from hydrates are very uncertain due to the lack of operational experience. Also uncertain are the prospects for developing technologies for commercial exploitation of methane clathrates as a source of energy. Nevertheless, such technologies might bear fruit at some stage and radically alter current perceptions regarding natural gas availability (IGU, 1997).

The only known production of natural gas from hydrates occurred in the Soviet Union with the partial development of the Messoyakha gas field, estimated to contain billions of cubic meters of methane hydrates. The production method involved injecting methanol to decompose the hydrates. Unfortunately, this project has been an economic failure because of the high cost of methanol (MacDonald, 1998).

Currently, attractive technological proposals are still outstanding on how methane hydrates could be recovered economically. However, given its enormous resource potential, it is plausible to expect that extraction methods will eventually be developed if long-term global gas demand warrants clathrate recovery. At present, there is little private-sector interest in better understanding the magnitude and cost dimensions of the methane hydrate resource, because conventional natural gas supplies are abundant on the time scales of interest to business (Williams *et al.*, 2000). But having such an understanding is important in decisions about relative RD&D priorities that relate to unconventional gas resource development and associated technologies in the near term. For this reason, as well as to better understand the theoretical potential of the hydrate resource and the attractions of natural gas as an energy carrier in general, there are several research projects underway in Japan, Russia, Norway, India and the US to examine the viability of future gas hydrate recovery (Collet *et al.*, 1998 and BGR, 1998). Most recently, the panels convened by the US President's Committee of Advisors on Science and Technology in the United States urged international collaborative RD&D in this area building on embryonic efforts already launched in Japan, Russia, and India (PCAST, 1997 and PCAST, 1999)

Abiogenic "Deep Gas"

The conventional theory of hydrocarbon occurrences within the Earth's upper crust is that they derive strictly from plant and animal debris transformed by geological processes into what is now considered to be fossil fuels. This notion has been challenged since its inception. For example, Mendeleyev (1877), who originated the periodic table of elements, concluded from the large-scale patterns of hydrocarbon occurrences that they originate from the depths of the Earth. Perhaps the most controversial theory is that of the abiogenic origin of methane, petroleum and coals (Gold, 1999).

According to this theory, hydrocarbons in the Earth's upper crust are relics of the material from which the Earth condensed billions of years ago. Gold (1999) argues that the biological molecules found in the "fossil" energy sources are the result of contamination by living creatures not from the decay of living creatures. Numerous arguments have been documented in support of his controversial theory. For example, if oil and gas are flowing upward from great depths and are under very high pressure, their upward flow cannot be arrested by any caprock. According to Gold (1999), the flow through a caprock obstruction is like that of a river crossed by a dam. The dam causes a lake to form, but the same amount of water will flow over the dam as reaches the lake in the long run. Thus, for example, the upwelling flow of hydrocarbons provides the recharging mechanism for the widely reported phenomenon that petroleum reservoirs seem to refill themselves. The mean rate of outflow from the deepest source of the hydrocarbons will not have increased due to the depletion of the reservoir. Rather, more of the fluids that already exist at intermediate depths will become accessible to fill the void. Furthermore, Gold (1999) argues that the upwelling methane is the main source of energy for life on Earth and the photosynthesis is a comparatively recent phenomenon. Living organisms use the upwelling flow of hydrocarbons throughout the upper crust. Gold (1999) calls this the "deep hot biosphere."

It is not necessary to be a supporter of the abiogenic origin of methane and petroleum formation to recognize that this speculative and controversial theory has the potential of transforming our perspective of the future availability of methane as a source of energy. The mere possibility of primordial origins of methane in the Earth's crust would render hydrocarbons a virtually "renewable" source of energy always to be replenished from below. This would also give a new spin to the question of how long will the methane age last because gas would no longer be considered as an "exhaustible" source of energy even over geological time scales.

Natural Gas Technologies

Natural Gas and Combined Cycle

Tremendous progress has been achieved in converting methane into electricity and other energy carriers. Wherever natural gas is readily available, it is the cheapest and cleanest source of electricity. The last decade or so has seen the dramatic breakthrough of combined-cycle gas-turbines (CCGTs). This technology involves expanding very hot combustion gases through a gas turbine with the waste heat in the exhaust gases used to raise steam for a steam turbine. The gas turbine can withstand much higher inlet temperatures than a steam turbine and this has allowed for considerable increases in overall efficiency. The latest designs can achieve efficiencies of over 60 percent. What is also impressive is that this figure has been rising by over one percent per year for over a decade. The low capital costs and high availability of combined cycle turbines also make them highly desirable by power station operators. Gregory and Rogner (1998) estimate that efficiencies of 71 to 73 percent are achievable within a reasonable period (on a lower heating basis, around 65 to 68 percent on a higher heating basis).

In contrast, 100 years ago the first power plants using steam engines for generating power resulted in overall conversion efficiencies of some five percent. Since then efficiency gains have been achieved though technological improvements of conversion efficiencies, for example, as the result of better materials, through fuel switching from coal to natural gas, and through changing from steam engines to turbines and combined-cycle schemes. This increase in efficiency is illustrated in Figure 15. It represents a factor 12 increase in conversion efficiency in about 100 years, corresponding to an improvement rate of about 2.5 percent per year. Suffice it to say that 12 times as much primary energy would be required today to produce current electricity needs in the world using the efficiencies prevailing 100 years ago. In fact, the effect of such low efficiency at current consumption levels would result in unsustainable environmental impacts at all scales.

The past 30 years in particular have witnessed steady improvements in steam and combustion turbine efficiencies as well as in overall system reliability, availability and maintainability. Environmental and economic concerns have also led to major development programs to improve the efficiency of electricity generation. Current technological measures primarily include further improvements to combined-cycle schemes. At the same time, environmental considerations often require the addition of flue-gas cleanup systems for pollutants such as nitrogen oxides and, in the distant future, perhaps also carbon scrubbers. Environmental controls have often been considered as a barrier to efficiency improvements in the past. Indeed, a drop in efficiencies by a few percent has been observed when technology responses to conventional designs consisted of add-on abatement measures only. These measures also increase capital requirements.

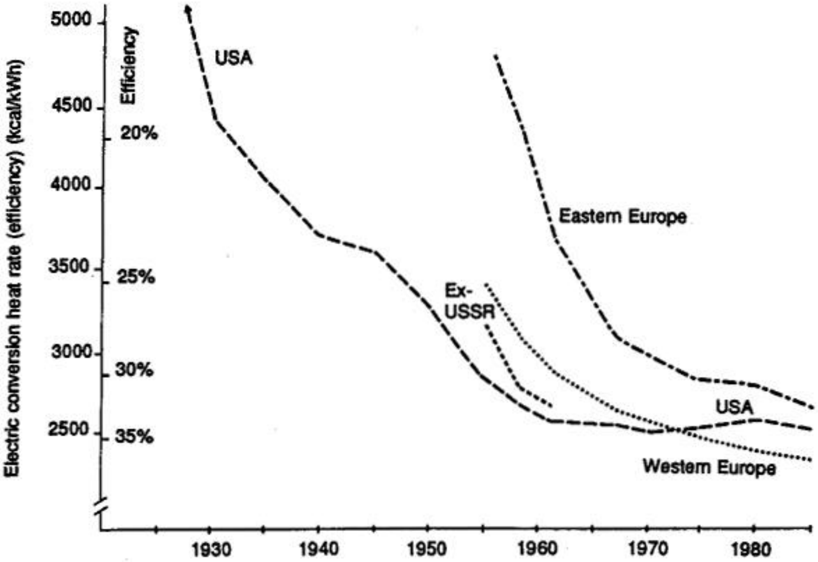


Figure 15: The historical improvements in electricity conversion efficiency in the USA and Western and the former Eastern Europe Source: Nakićenović, 1993.

Recent innovative plant design and combined-cycle technology, however, have succeeded in both efficiency improvements and emission reductions over and above those directly linked to the efficiency factor (Nakićenović, 1993). Further efficiency improvements of a few percentage points are expected in the next years for combined-cycle. The emissions of such plants are already generally very low, but further improvements are still possible. For example, premixing of fuel and air in a hybrid burner avoids temperature peaks during combustion and thus reduces nitrogen oxides emissions significantly (Valenti, 1991). New smaller-scale turbine designs, such as the mini and micro turbines and small hypersonic-gas turbines, promise even more flexibility in operation and siting together with very low emissions levels.

These recent developments favor natural gas turbines and combined-cycle power plants becoming the technology of choice throughout the world because of their cost and environmental advantages, very high efficiencies and modularity. In conjunction with the high hydrogen-to-carbon ratio of natural gas, high efficiencies lead to low emissions of all pollutants, including carbon dioxide, while the high modularity is compatible with the flexibility required in competitive privatized energy markets. Figure 16 shows the rapid penetration of combine-cycle technology in global electric generating capacity during the last 25 years. From 1975 to 1985 global installed generating capacity declined by more than a half from some 120 to about 50 GWe. Much of this decline occurred in coal-fired steam-cycle plants while most of the additional capacity increase since 1985

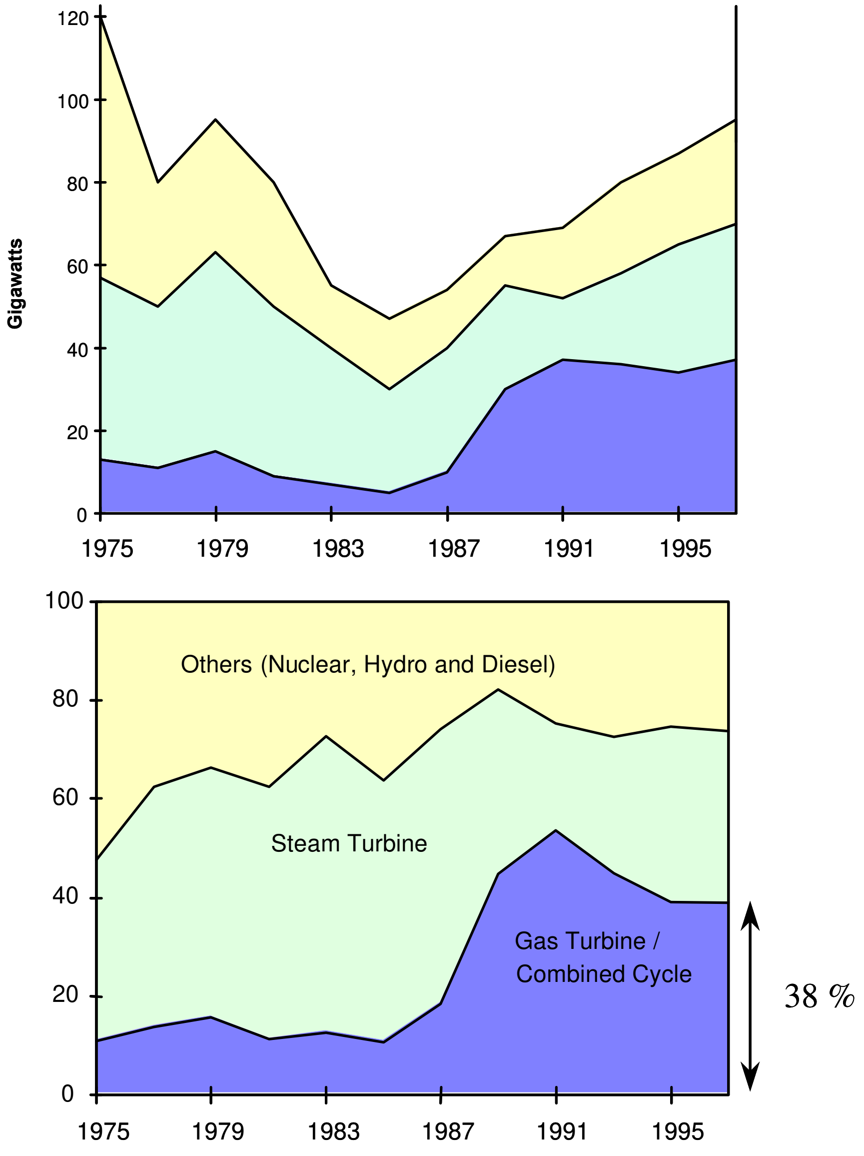


Figure 16: Global installed electric generating capacity, historical development from 1975 to 1997; (top) total installed capacity by type of generation in GWe and (bottom) the relative shares by type of generation in percent. Source: Financial Times, June, 1997.

was due to the vigorous expansion of natural-gas combined-cycle plants. Today, they constitute some 40 percent of all electric power plants in the world.

Combined-cycle technology represents a hedge against the uncertainty of future environmental policy priorities, and also represents an effective least-regret cost investment strategy associated with hydrocarbon fuels. That is, the economics of combined-cycle technology do not hinge on the availability of low-cost natural gas or fuel oil, or on the possibility of restrictive environmental policies. In fact, most clean coal technologies also involve the marriage of gas turbines and coal or coal-based clean fuels (Bajura and Webb, 1991).

Methane and Oxygen Gas Turbines

Another clean fossil technology is the combustion of natural gas (or synthesis gas from coal or pulverized coal) in a mixture of oxygen and recycled flue gases. Thus, carbon dioxide as the main constituent of the flue gases, becomes the working fluid of the turbine. The excess carbon dioxide would be either vented or stored (after compression and drying). This scheme would involve a combined-cycle power plant with oxygen being fed from an air separation plant and flue gas recirculation (Bolland and Sæther, 1992). The amount of oxygen has to be controlled since combustion in pure oxygen can lead to excessive temperatures. The efficiency penalty for an air separation plant to produce the required oxygen is about ten percentage points. The overall plant efficiency would be in the range of about 30 percent (Abele *et al.*, 1987).

An advanced version of this system would operate at high temperatures and pressures achieving very high conversion efficiencies. This is conceivable if material problems could be solved since the oxygen is delivered at high pressure (in the region of about 50 Bar) from the separation facility. Natural gas directly from pipelines also comes at high pressures. Another advantage is that the carbon dioxide and steam stream from the turbine would also be at high pressure, offering the opportunity for carbon removal without the need for additional equipment.

Magneto-Hydrodynamic Generators

Instead of a rotating metallic conductor as used in conventional mechanical-electric generators, the magneto-hydrodynamic (MHD) generator forces an electric conducting fluid through a perpendicular magnetic field at high velocity. The fluid generates an electric field by passing through the magnetic field. Electrodes constituting the container wall draw the current. The conducting fluid is either an ionized gas or a liquid metal. In the case of coal, the fluid is the ionized combustion gas (Chapman and Johanson, 1991).

In a combined-cycle configuration, MHD would replace the gas turbine that generates the steam for the bottoming cycle. The steam boiler associated with the MHD generator is distinctly different from a standard boiler: the gases exiting the generator are fuel-rich. This requires a secondary combustor so that the bottoming cycle must be equipped with an exhaust gas clean-up system. The overall efficiency of this combined-cycle arrangement is approximately 55 percent.

Carboniferous Fuel Cells

The major potential competitor to CCGT technology is the fuel cell that may offer similar efficiencies at much lower plant sizes making them ideal candidates for distributed combined heat and power generation. Another promising fuel cell application is vehicle propulsion. In the past, high costs and durability problems restricted their use to highly specialized applications, such as electricity generation in space. Recent advances in fuel cell technology, however, have improved the prospects for fuel cell applications to the point of commercial availability (Penner *et al*., 1995).

Fuel cells offer significant efficiency increases. In contrast to thermal power plants, fuel cells convert the chemical energy of the fuel into electricity without first burning the fuel to produce heat. As a result, they have the potential of very high thermodynamic efficiencies and low levels of emissions. The conversion efficiency from hydrogen to electricity could be as high as 70 percent. Another advantage is that they offer the possibility of small and large-scale applications. Much attention is being given to the development of fuel cells for power production, in the range of more than 200 MWe, by integration with steam or gas turbines. Such systems would be competing with advanced coal technologies and combined-cycle natural gas generation.

Although operating internally on hydrogen, fuels cells can be fueled with an hydrocarbon fuel such as be natural gas, methanol, gasoline or even coal. Before entering the fuel cells, these fuels would be converted on-site or on-board into hydrogen via steam reforming, partial oxidation or gasification and hydrogen separation. In the longer run, and to make fuel cells truly zero-emission devices, neat non-fossil derived hydrogen supplied and stored as compressed gas, cryogenic liquid, metal hydrate or other storage schemes would replace hydrocarbon fuels.

In addition to the carbon-free fuel cells, fueled by hydrogen, there are two fuel cell designs suited for clean hydrocarbon fuel utilization. The fuel cells suitable for hydrocarbon fuel use typically operate at high temperatures and are less sensitive to carbon or impurities. It is unlikely that these fuel cells would be able to utilize coal directly in the foreseeable future. In the meantime, the dominant fossil fuel cells will be fueled by natural gas, methanol or synthesis gas produced from coal. Two promising fossil fuel cell designs are the molten carbonate fuel cell and the solid oxide fuel cell. The first design utilizes an electrolyte consisting of molten salts operating at 650°C, opening the possibility of using carbonaceous fuels and internal reforming. Hydrogen is immediately oxidized electrochemically to water vapor, which, in turn, drives the shift process. If natural gas is used as fuel feed, internal reforming requires the presence of a reforming catalyst, eliminating the cost of an external steam methane reformer. Moreover, sufficient steam is available to run steam turbines in a bottoming cycle with overall efficiencies as high as 60 to 65 percent for synthesis gas and natural gas, respectively.

Solid oxide fuel cells operate at temperatures in the vicinity of about 1000°C. When fueled directly by natural gas they do not require the presence of a catalyst. The high operating temperature and some excess steam suffice to stimulate instant reforming. They can operate equally well on hydrogen and carbon monoxide, individually and jointly. Hence, synthesis gas from methanol reforming or coal gasification can easily be used. However, the presence of carbon monoxide generally lowers the efficiency by about ten percentage points. The advantage of solid oxide cells is that they have a relatively high tolerance to impurities such as sulfur, allowing the use of untreated coal-based synthesis gas.

Both the molten carbonate and solid oxide fuel cells are still under development and to reach full commercialization need to provide proof of reliability. Here again, natural gas holds the promise of achieving even higher conversion efficiencies compared with other competing sources of energy.

Technological Change

Technological Learning and Diffusion

Technological change increases the performance of energy systems, decreases their costs and can reduce environmental impacts at all scales. Thus, technological change is a fundamental driving force of economic development and the evolution of energy systems.

Technological change can be seen as a learning process. The early development of each new technology involves experimentation and testing before possible applications are sufficiently refined to attempt commercialization and entry into the competitive market place. In the beginning, new technologies are often inferior, compared to their mature alternatives, in economic and often also technical performance, but hold the advantage of providing a new service or performing new tasks not possible with traditional methods. Before economic attractiveness can be achieved, costly investments are made to improve the economic performance of a new technology. This is the learning aspect and the process really ever stops. Technologies are improved continuously from the time of their inception in the laboratory to eventual senescence. However, it is an interactive process across all stages of development. The emphasis in the recent innovation literature is now placed more on a "chain-link" model of technology innovation, exploiting interactions between private and public RD&D efforts and the various stages of production and marketing. Lane and Maxfield (1995) emphasize the role of "generative" relationships in creativity and technological learning.

Technological learning can be illustrated for many technologies by so-called experience or learning curves. The first examples came from aircraft manufacturing where it was observed that production costs decline in proportion to cumulative output as measured by the total number of aircraft manufactured since the start of production. With every doubling of cumulative production, costs decline a fraction. A typical learning curve is shown in Figure 17 for gas turbines in electricity generation. It consists of two segments. The first corresponds to the entry into niche markets where gas turbines had an inherent advantage despite high costs (such as generation of peak electricity). This application in niche markets lead to early commercialization and a significant reduction of costs. The second segment is the competitive phase, which led directly to the pervasive diffusion of gas turbines; today, gas turbines are the preferred technology for electricity generation. The marginal cost per new unit of capacity has declined dramatically with the cumulative increase in installations. For much of this period, the new technology was costlier than its alternatives and represented an investment rather than profit taking activity. We have estimated that, together with research, development and deployment (RD&D) efforts, the total investment approached some US$5 billion before the new technology became competitive on a cost basis. This figure does not include any of the

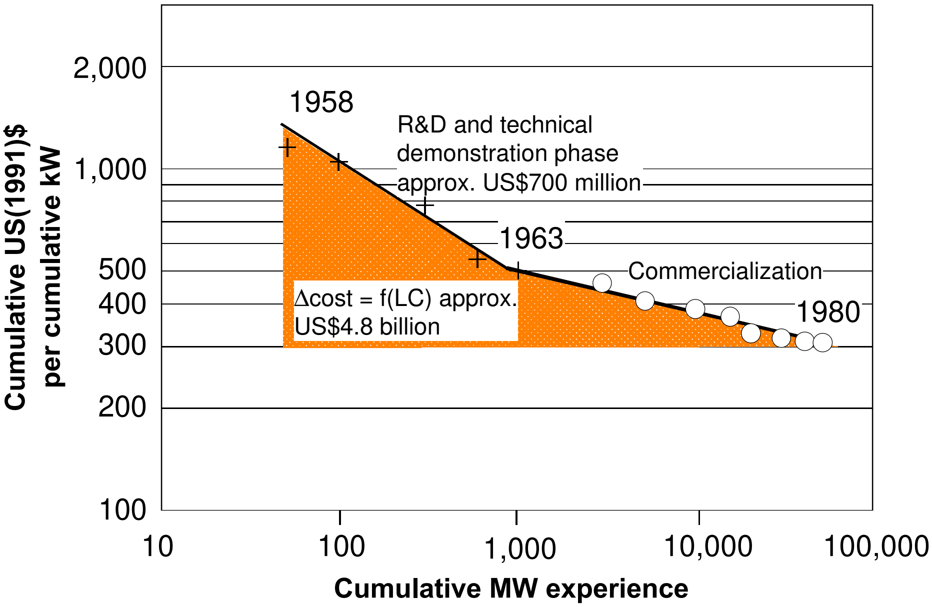


Figure 17: Reduction of investment costs for gas turbines for electricity generation as a learning process expressed in specific investment costs, in US(1991)$ per kWe installed capacity, versus cumulative installed capacity in MWe on double logarithmic scale.

original investment in aircraft jet engines before first derivatives were adapted for electricity generation. The figure refers only to the costs incurred by one manufacturer, its clients, and subsidies, if any (e.g. government programs).

Figure 18 contrasts the learning curve of the gas turbines with two new renewable electricity generation technologies – wind power and photovoltaics. Both technologies display rapid learning albeit at high costs. Wind power can be competitive today under special conditions – at sites with steady strong breezes and often with subsidies. Photovoltaics are competitive only in very specialized (and small) market niches such as power sources for remote mountain huts. The question is whether these two new technologies will become economically competitive with more conventional alternatives as installed capacity rises – in other words, whether the learning curves can be extended, as shown, by public and private investors willing to speculate that further (costly) investments will sufficiently reduce costs in the future.

In other words, improvements in the performance and a reduction in the costs of new technologies are not “autonomous” processes; rather, they are an outcome of accumulated knowledge mainly by learning-by-doing. The process of competition in niche and then in wider markets is, indeed, marked by continuous marginal innovations that improve the performance and lower the costs of a basic, core technology.

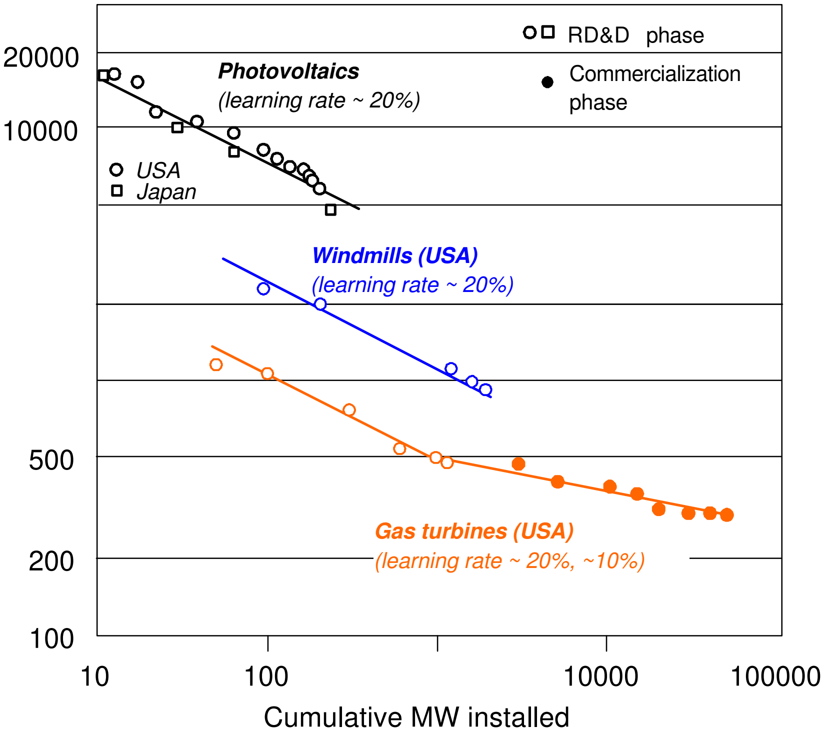


Figure 18: Reduction of investment costs for gas turbines, windmills and photovoltaics for electricity generation as a learning process expressed in specific investment costs, in US(1991)$ per kWe installed capacity, versus cumulative installed capacity in MWe on double logarithmic scale. Source: Nakićenović *et al.*, 1998a

Continuous improvement of technologies beyond the research phase is an important prerequisite for their future competitiveness in the market place.

As new technologies evolve they replace the more traditional alternatives. This is the case for single technological innovations such as the replacement of horses by cars or records by compact discs. Examples of technological substitution in the energy area are the replacement of coal by oil as the dominant energy source, and the replacement of steam engines by steam turbines in electricity generation. Clearly the replacement of horses by cars and other technological changes in energy end use are related to corresponding transformations in the energy system. Technologies are related to each other as these examples suggest and often they form whole clusters of innovations that interact with each other. They are best characterized by phrases such as the age of coal, steam, steel and railways. The emergence of such a cluster of new energy technologies would be required for a transition first to the methane age and later possibly also to the era of hydrogen and electricity.

Together, the technological learning and diffusion clusters form the process of change that increases productivity, performance, efficiency and environmental compatibility of human activities and thus fundamentally transform our societies and way of life. This process is not autonomous and requires investments and appropriate institutions to mediate and enhance the development of new technologies. Investments are required for early development of new technologies, for experimentation associated with early deployment, for development of niche markets and for technological learning along the experience curves.

Understanding Technological Change

The future direction and rates of technological change are uncertain and therefore need to be explored by considering a range of alternative future developments. Technological change is embedded in the cultural, social and economic environment and goes beyond the innovating agents in many ways as described, for example, by Grübler (1998a), Landes (1969), Rosenberg (1982, 1994, 1997) and Rostow (1990). Innovations are highly context-specific, emerging from local capabilities and needs, evolving from existing designs, and conforming to standards imposed by complementary technologies and infrastructures. Successful innovations may spread geographically and also fill much broader functions. The classic example is the steam engine, developed as a means of pumping water out of deep mines in Cornwall, England, but to become the main source of industrial motive power and the key technology in the rail revolution world-wide. Another example related to natural gas is the development of aircraft gas-turbines (to replace piston engines) that were subsequently modified to become the prime movers of choice in electricity production after many improvements. Therefore, future technological systems need to be assessed in broader contexts of alternative developments and alternative combinations that might lead to new technology clusters.

Numerous examples can be used to demonstrate the messiness, or complexity, of innovation processes (e.g., Grübler, 1998a; Rosenberg, 1994). But even if the innovation process is messy, at least there are some general features or "stylized facts" that can be identified (Dosi, 1988; Grübler, 1998):

- the process is fundamentally uncertain and outcomes cannot be predicted;
- innovation draws on underlying scientific or other knowledge;
- some kind of search or experimentation process is usually involved;
- many innovations depend on the exploitation of "tacit knowledge" obtained through "learning by doing" or experience;
- technological change is a cumulative process, depending on the history of the individual or organization involved; and
- different combinations of new technologies are possible and can enhance the emergence of new clusters.

Because of these six features, some individuals, firms or countries are better at innovating than others. Innovators must be willing and able to take risks; they must have some level of underlying knowledge; they must have the means and resources to undertake a search process; they must perceive opportunities of innovation such as new technology clusters; they may need relevant experience; and they may need access to an existing body of technology. Many of these features introduce positive feedback into the innovation process, so that countries or firms that take the technological lead in a market or field can often retain that lead for a considerable time.

Technological change may be supply-driven, demand-driven, or both (Grübler, 1998). Some of the most radical innovations are designed to respond to the most pressing perceived needs. Many technologies were developed during wartime to address resource constraints or military objectives. On the other hand, some innovations (e.g., television) are generated largely through curiosity or the desire of the innovator to meet a technical and intellectual challenge. Market forces (including those anticipated in the future) can act as a strong stimulus for innovation by firms and entrepreneurs aiming either to reduce costs or to gain market shares.

All innovations require some social or behavioral change (OECD, 1998). At a minimum, changes in production processes require some change in working practices. Product innovations, if they are noticeable by the user, demand a change in consumer behavior and sometimes in consumer preferences. Some product innovations – such as those that result in faster computers or more powerful cars – provide consumers with more of what they already want. Nevertheless, successful marketing may depend on consumer acceptance of the new technology. Other innovations – such as alternative fuel vehicles or compact fluorescent lights – depend on consumers accepting different performance characteristics or even redefining their preferences.

An important perspective on technical change is that of the end-user or consumer of products and services. Technology can be seen as a means of satisfying human needs. Several conceptual models have been developed to describe needs and motivation although their empirical foundations are weak (Douglas *et al.*, 1998; Maslow, 1954; and Allardt, 1993). In many cases, a given technology helps to satisfy several different types of need. This is particularly evident in two of the most significant areas of energy use: cars and houses. This tendency of successful technologies to serve multiple needs contributes to lock-in by making it harder for competing innovations to replace them fully. Hence, many attempts to introduce new, energy efficient or alternative fuel technology, especially in the case of the car, have failed because of a failure to meet *all* the needs satisfied by the incumbent technology. Different individuals may interpret the same fundamental needs in different ways, in terms of the technology attributes they desire (OECD, 1996). Deep-seated cultural values or “metarules” for behavior can be considered to be filtered through a variety of influences at the societal, community, household and individual level (Douglas *et al.*, 1998 and Strang, 1997). Commercial marketing of products usually aims to adjust the filters, encouraging people to associate their deep-seated values with specific product attributes (Wilhite, 1997). These associations are likely to be more flexible than the values themselves, providing a potential source of future changes in technology choice.

Technology diffusion is an integral part of technical change. The uptake of a technology that is locally "new" can be viewed as an innovation. Often, when technology is adopted, it is also adapted in some way, or used in an original way. Just as technology development is much more complicated than the simple exploitation of scientific knowledge, Rosenberg (1997), Wallace (1995), Landes (1969) and others have emphasized that technology diffusion is highly complex. Wallace emphasizes the importance of an active and creative absorption process in the country taking up the new technology. The implication of this complexity is that there are no general rules for "what works." The process of technology adoption is as context-dependent as that of the original innovation. Rosenberg (1997) also emphasizes the role of movements of skilled people in the diffusion of technology. Transnational firms often play a strong role in such movements. Other factors influence the technology transfer process, including differences in economic development, social and cultural processes as well as national policies such as protectionist measures.

Grossman and Helpman (1991), Dosi *et al.* (1990) and others have attempted to capture some of the complexities in "new growth" and "evolutionary" economic models. They have been able to demonstrate the flaws in some of the simpler solutions to technology diffusion often advocated – for example, they show how free trade might sometimes exacerbate existing gaps in institutions, skills and technology.

The complex interactions underpinning technology diffusion may give rise to regularities at an aggregate level. The geographical and spatial distribution of successive technologies displays patterns similar to those found in the succession of biological species in ecosystems, and also in the succession of social institutions, cultures, myths and languages. These various processes have been analyzed, for example, in Campbell (1959), Marchetti (1980), Grübler and Nakićenović (1991), and Grübler (1998).

Many attempts to endogenize technical change in economic models rely on a linear approach where technical change is linked to the level of investment in R&D (e.g., Grossman and Helpman, 1991and 1993). More importantly, this model has been the basis of many governments' strategies for technological innovation. As mentioned above important additional features of technological change include uncertainty, the reliance on sources of knowledge other than R&D, "learning by doing" and other phenomena of "increasing returns" that often lead to technological "lock in" and hence great difficulties in introducing new alternatives.

These features can be captured to some degree in models and a great deal of experimentation has taken place with different model specifications. However, the first feature, uncertainty, means that models can never be used to predict the process of technical change. This uncertainty stems partly from lack of knowledge: the outcomes of cutting-edge empirical research simply cannot be predicted. However, it also stems from the complexity of the influences on technological change, and in particular the social and cultural influences that are extremely difficult to describe in formal models. Recent attempts to endogenize technical change in energy and economic models have been made by several researchers, many of whose work is reviewed by Azar (1996). Optimization models usually treat technology *development* as exogenous but technology *deployment* as endogenous and driven by relative technology life-cycle costs. A few GHG emission projection models (e.g., Messner, 1997) have been developed to incorporate "learning by doing": the reduction in technology costs and improvement in performance that can result from experience (Arrow, 1962). Models have also been developed that explicitly include technological uncertainty to analyze robust technology policy options (e.g., Messner *et al.*, 1996 and Grübler and Messner, 1996). Others have been developed more recently to incorporate the effects of investment in knowledge and R&D (Goulder and Mathai, 1998). Economists and others studying technological change have developed models that take a variety of dynamics into account (Silverberg, 1988). Some models focus on technologies themselves, for example examining the various sources of "increasing returns to scale" and "lock-in" (Arthur, 1994 and 1989). Others focus on firms and other decision-makers, and their processes of information assimilation, imitation and learning (Nelson and Winter, 1982; Silverberg, 1988; and Andersen, 1994). Few of these dynamics, apart from "increasing returns to scale", have been applied to the projection of GHG emissions from the energy sector.

Technological Spillovers and Clusters

Technologies are related to each other. For example, jet engines and gas turbines for electricity generation are related technologies. In fact, the latter were initially derived from the former. These kinds of relationships among technologies are frequent. They imply that improvement in some of the technologies may be transferable to other related technologies. The improvements in one area that lead to benefits in other areas are often referred to as spillover effects. In case of related technologies this is a real possibility. For example, consider the different applications of fuel cells such as for stationary electricity generation and for vehicle propulsion. These fuel cells are different but they are related in the technological sense so that improvements in one technology may lead to improvements in the other. In this new approach to model technological learning and uncertainty, we explicitly consider the possibility of such spillover effects among energy technologies.

However, operational implementation of spillovers is not trivial. One of the important barriers is the lack of a technology "taxonomy". Presumably, the possibility of positive spillovers from technological learning is higher for technologies that are similar compared to those that are not. Thus, some kind of measure or metric of technological "proximity" or "distance" is required even though a genuine taxonomy does not exist. A number of proposals have been made that could conceivably lead to the development of a taxonomy in the future (Foray and Grübler, 1990). Instead of venturing here in more complex representations of technology relationships, we simply assume that there is basically two explicit types of spillover effects. One is indirect through the connections among energy technologies within the energy system. For example, cheaper gas turbines mean cheaper electricity so that *ceteris paribus* this could favor electricity end-use technologies for providing a particular energy service compared to other alternatives. The other effect is more direct. Some technologies are related through their "proximity" from a technological point of view as suggested by the example of stationary and mobile fuel cells. For example, Table 4 shows "clusters" of technologies, which may lead to spillovers from learning in one technology to another. Within clusters, the spillover effects are assumed to be strong and weaker across clusters. Each cluster consists of technologies that are related either because they are technologically "close" (i.e., are similar) or enable each other through their connections within the energy system (Gritsevskyi and Nakićenović, 2000). All of the technologies shown could be combined to form different clusters in future energy systems. Which might be successful cannot be anticipated with certainty, but it is evident that many of the promising methane technologies are consistent with hydrogen and electricity as the dominant future energy carriers.

Future Natural Gas Transport

Natural gas transport and distribution infrastructures, and combined-cycle technology constitute the core of current methane technologies. Any future strategy needs to consider evolutionary changes that would lead to a more pervasive diffusion of these technologies, as well as the gradual introduction of new advanced methane technologies. These need to extend over the whole energy system, from resource extraction to end use. The assessment of methane resources has indicated that they need not constitute a major global constraint to the future expansion of gas use. Resources are large enough to fuel even the highest of all scenarios considered in this assessment that has the appropriate name the "methane age." However, new technologies need to be developed to transfer these abundant resources into economically viable reserves. The currently estimated reserves are likely to last a few decades into the future, and with the less aggressive role for natural gas in some scenarios, perhaps up to six or seven decades. However, scenarios like the "methane age" presuppose economic extraction of exotic sources of methane such as hydrates and aquifers. Other gas-intensive scenarios, such as the IIASA-WEC A3 and SRES-MESSAGE-AG, require quantities of gas that by far outpace currently estimated global reserves. What is crucial is that the limitations in future gas availability appear not to be dominated by geology but by human ingenuity in developing and connecting future gas deposits with consumption centers. This requires development of elaborate infrastructures throughout the world. At the same time, new

Table 4: Technologies with possible increasing returns to scale grouped into 10 technological clusters. Source: Gritsevskyi and Nakićenović, 2000.

Name	Expected Learning Rate, **%**	Cumulative output at base year, Gwyr[1]	Expected Lifetime, yr	Technologies
Fuel cells in Transportation[2]	20	0.01	10	Hydrogen, liquid hydrogen, methane and methanol based fuel-cells (FC) in transportation
Decentralized fuel cells (Industrial and Residential & Commercial sectors)[3]	20	0.1	20	Hydrogen and methane based FC in Industrial and R&C
Centralized fuel cells in energy sector[4]	20	1	30	Methane and coal based large scale FC,
Reforming of methane	25	0.2	20	Steam reformers for producing hyrogen from methane with carbon capture (SR)
Hydrogen and methane infrastructure	10	1	40	Hydrogen and liquid hydrogen transportation and distribution infrastructure, 2 technologies
Solar to hydrogen	10	1	20	Solar to hydrogen production
Nuclear high-temperature	10	10	40	Nuclear high temperature reactors with hydrogen output through thermolysis or methane reforming
Wind	15	2	30	Wind power generators, 1 technology
Synthetic fuels and hydrogen production	20	3	30	Synthetic fuels and hydrogen production from biomass, gas and coal,
Liquid hydrogen production	10	0.5	30	Hydrogen liquefaction,

[1] Part of model assumptions. In many cases, there is no reliable statistics for global cumulative output.

[2] Contribute to other fuel cells clusters with weight and accelerated by input from stationary units with weights 0.1 and 0.01 for decentralized and centralized installation correspondingly.

[3] Contribute to other fuel cells clusters with weight 0.5 to centralized units and 0.1 to transportation and accelerated by input from centralized units with weight 0.1 and with 0.5 for transportation.

[4] Contribute to other fuel cells clusters with weight 0.1 to decentralized units and 0.01 to transportation and accelerated by input from decentralized and transportation units with weight 0.5

transport systems and connections would allow those parts of the world with limited methane resources to also obtain the clean, convenient and affordable energy services offered by methane technologies.

Future infrastructural requirements for a wider use of methane are perhaps most daunting from a current perspective compared to all other “enabling” technologies. Gas pipelines require high capital costs, relatively long pay-back times compared to other investment opportunities, and stable connections across borders. They represent long-lasting commitments for both producers and consumers. This nature of infrastructures can be both a barrier and a promoter of diffusion. Once connections are made, they tend to promote further intensification of existing, and construction of new, connections. A case in point are the pipelines that connect Eastern Siberia with Europe. In general, gas resources are located some distance from consumption centers. The feasibility and cost effectiveness of energy transportation over long distances is a key factor to successful market penetration of not only gas but also other hydrocarbon fuels and electricity.

Figure 19 shows possible future natural gas trade across continents in the gas-intensive SRES-MESSAGE-A1G scenario in 50 years. The main gas producing regions, Siberia and the Caspian, deliver some 63 EJ of energy to Europe and Asia. This compares with 8 EJ exported from East Siberia to Europe in 1996 (Energy Charter, 1998). In fact, the scenarios underestimate the true gas trade by a large factor. For example, the global oil trade was 68 EJ (BP, 1998) compared to 46 EJ intercontinental oil flows in the scenario. What is shown are only intercontinental flows, but many regions would have large internal gas flows, such as those from Siberia to European Russia, or from the North Sea to Europe. Thus, the figure underestimates the actual gas flows between extraction and consumption. The figure shows the continents proportional to their future energy

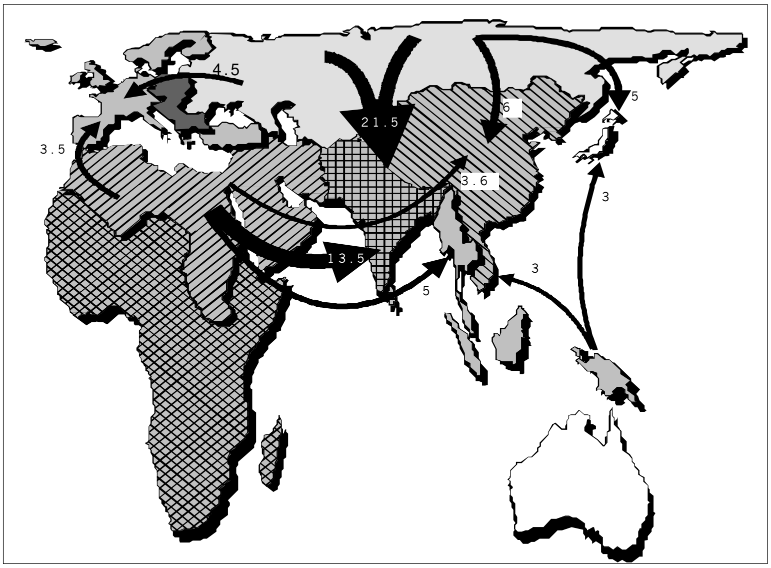


Figure 19: Intercontinental natural gas trade flows within Eurasia in 2050 for a gas-intensive SRES-MESSAGE-A1G scenario. Flows denote pipelines and LNG routes, width of trade "arrows" is proportional to gas flows, flows are expressed in EJ per year, areas of the world regions are proportional to primary energy consumption in 2050. Data sources: Roehrl and Riahi, 2000 and Nakićenović *et al.*, 2000a.

demand rather than land area, indicating how large the energy demands might be in Asia and Africa in five decades. A small part of this future demand is due to population growth, most of it is due to development. Clean, convenient and affordable energy is a prerequisite for development. Africa and Asia are estimate to have some two billion people today that do not have access to commercial energy and live in poverty. The challenge is monumental and Figure 19 shows some implications of what would be required for natural gas to make a major contribution toward the solution.

Today, more than 75 percent of the world gas trade flows are transported via gas pipelines. For long distances, thin-walled, large diameter, high pressure steel pipes are used. Their operation pressure lies between 35 and 70 bar with a diameter of up to 130 cm. Figure 20 compares the increase in gas pipeline length and gas consumption in the US during the last 70 years. The relationship is quite strong until the 1970s: infrastructure length increased in proportion to consumption growth. After the oil price shocks the relationship changed somewhat. Nevertheless, it is evident that infrastructure growth needs to keep pace with increases in consumption. As pipeline technologies improve and gird expands, this relationship is likely to change but the general trend is likely to be maintained. Transportation capacity roughly grows with the cube power of the pipeline diameter. Hence, very large pipes require extremely large markets, which are emerging through the concentration of world population in energy intense megacities in the scenarios that lead to the international gas flows shown in Figure 19.

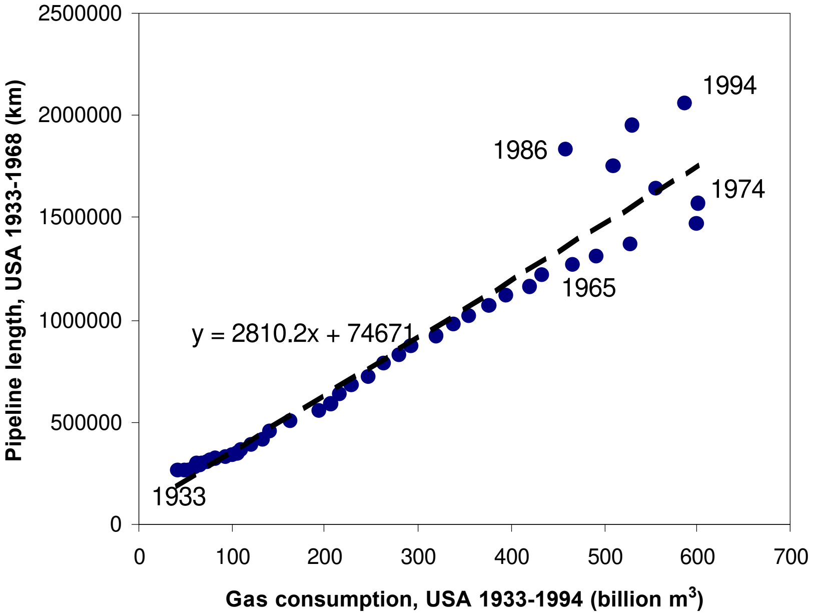


Figure 20: Evolution of the relationship between length of pipeline network and natural gas consumption in the US, historical development from 1933 to 1994, length of pipelines in km and gas consumption in billion m^3.

Extrapolating this relationship to the global gas flows illustrated in Figure 19 implies a pipeline infrastructure of about 70 million km, the "methane age" scenario would require twice as much with some 140 million km. The actual length might be shorter than indicated by the rough extrapolation, given the above caveats concerning increases in pipeline carrying capacities for large networks.

Today, about one quarter of global gas trade is by LNG because it can be transported in ships that offer flexible routing compared to pipelines. For distances up to 2000 km the costs of LNG transportation are substantially higher than those of pipelines. With increasing distance LNG becomes more competitive and at distances over 4000 km it is the cheaper option. LNG is stored at a temperature of -167ºC and atmospheric pressure. The energy density of LNG is about 600 times that of natural gas at standard conditions. Another possibility for the future would be to transport methane in ships in the form of clathrates. The energy density of methane clathrates is about 170 times that of natural gas at standard conditions. Once produced say in gas fields in cold regions, they need only atmospheric pressure and relatively mild temperatures (-5ºC) compared to LNG so that they are likely to be competitive as a means of methane transport over long distances. The energy density is four times lower compared to LNG so transport vessels would have to be four times larger but would require very modest cooling.

Future Conversion Technologies

Combined-cycle technology was a major factor contributing to the success of methane technologies and making natural gas the fuel of choice. In the future, gas turbine and associated technologies are likely to provide competitive and efficient conversion of methane into electricity. However, conversion efficiencies can be expected to improve as combustion temperature and turbine pressures continue to increase. The improvement would extend over the whole range of scales and related technologies from micro-turbines suitable for portable powers sources to extremely large units suitable for delivering base-load to transcontinental grids. For example, the methane oxygen combined-cycle technology based on carbon dioxide as the working fluid could reach efficiencies of perhaps 59 percent assuming inlet temperatures of 1,300 ºC and pressures of 400 bar. Clearly, progress needs to be made in developing new materials to sustain high temperatures and pressures before this may be possible. However, such new methane conversion technologies would have a decided advantage of being scalable to very large units (Jericha *et al.,* 1995 and Jericha, 1998). From today's perspective this might not appear to be a great advantage in the competitive markets. However, in some areas of the world, both the energy transport infrastructure and conversion technologies need to be constructed in large increments every year during the next five decades and more. For example, China's power requirements imply an annual growth of installed capacity of some 30 GWe. In conjunction with large gas and electric grids, such large units may indeed offer decisive advantages of economies of scale required for providing clean and affordable energy into future mega-cities, particularly in Asia.

Another great advantage of such future technologies would be that carbon dioxide could be sequestered directly as a part of the conversion process. It would be available at high pressures at the power plant site and could be piped for storage to aquifers or depleted natural gas fields. An extremely attractive scheme could involve the extraction of methane from hydrates offshore, transport of electricity, and storage of sequestered carbon in the form of carbon dioxide clathrates in the same deposits below the ocean from which the methane was extracted.

Fuel cells are another attractive technology for electricity generation from methane. They may compete with combined-cycle technology over some generating capacity scales. However, they are very attractive as small-scale mobile power sources for vehicles. It is quite possible that future automobiles will rely exclusively on fuel cells for propulsion.

Future Clusters of Methane Technologies

Another possibility would be to combine different technologies into new polygeneration and integrated schemes. For example, new combined-cycle systems that use high-temperature fuel cells to replace combustors are conceivable. What is more important, however, are combinations of technologies in the future energy systems that would achieve high “spill-overs” and jointly enhance each other’s market penetration rates and thus eventually lead to the methane age. This would require the convergence of many different driving forces. They range from economics and social acceptance to environmental considerations.

Many scenarios in the literature consider the replacement of current by future technologies and how they may combine to form new technology clusters. Figure 21 indicates the possible timing of introduction of new natural gas electricity-generation technologies across a range of scenarios including the IIASA-WEC A3 and SRES-MESSAGE-AG (Nakićenović *et al.*, 1998a; Riahi and Roehrl, 2000; Nakićenović *et al.*, 2000a). The replacement of conventional oil and natural gas power plants is competed in all of these scenarios between the 2020s and 2030s. In contrast, the conventional coal power plants last in some world regions that are rich in domestic resources through the 2050s. During the same time period combinations of new electricity-generation technologies diffuse throughout the world. They range from fuel cells and integrated gasification combined cycle to natural gas combined cycle with carbon removal and disposal. Dashed lines indicate the technologies that are particularly favored by policies designed to reduce global carbon dioxide emissions. The length of the lines indicate the range of introduction of new technologies across the scenarios.

Combined-cycle technology indicates that methane can be the most economic fuel. In a similar fashion methane powered fuel cells might turn out to be a cheaper source of power compared to other hydrocarbons, such as gasoline and methanol, that are being considered today as the main alternatives. Natural gas is cheaper than both gasoline and methanol and performs just as well as a fuel. Favorable economics are certain to enhance the social acceptability of methane technologies. In fact, natural gas has already found its way into most of the homes of the affluent societies so that there is no reason to assume this would not happen throughout the rest of the world once economic and other conditions are suitable. As energy densities increase in urban metropolitan areas, grid oriented energy carriers such as electricity and gas become most important supply options. A part of the reason is that they have low adverse environmental impacts at point of end use compared to other alternatives. Electricity does not have any material emissions and the combustion of methane with advanced technologies has the lowest emissions of all hydrocarbon fuels. Emissions of nitrogen oxides can be also reduced to a minimum. However, the combustion of all hydrocarbons leads inherently to carbon

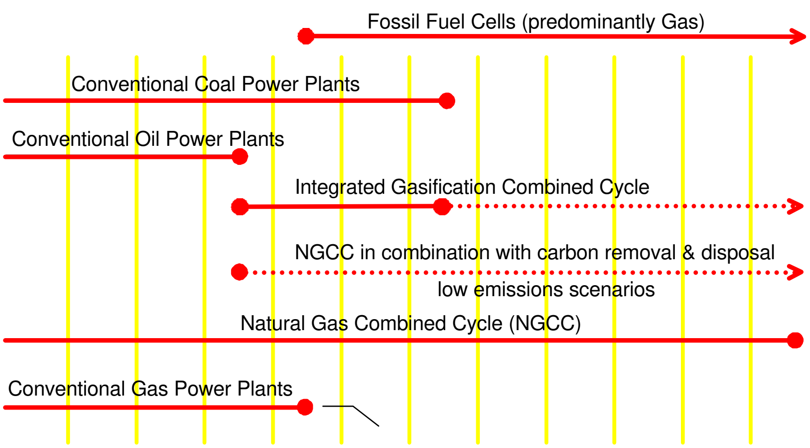


Figure 21: Timing of introduction of new electricity-generation technologies and phase-out of traditional technologies across global energy scenarios including methane-intensive the IIASA-WEC A3 and SRES-MESSAGE-AG. The length of the lines indicate the range of introduction of new technologies across the scenarios and dashed lines the technologies favored by reduction of carbon dioxide emissions. Data sources: Nakićenović *et al*., 1998a; Riahi and Roehrl, 2000; and Nakićenović *et al*., 2000a.

dioxide emissions. Carbon dioxide emissions reduction is important as it is the greenhouse gas with the highest contribution to anthropogenic radiative forcing. In addition, it is crucial that all methane technologies be "leak-proof" because methane is a very potent greenhouse gas. In any case it is better to combust methane rather than to release it into the atmosphere from the climate change point of view.

On balance, environmental considerations are likely to offer a decisive advantage to methane over other competing technologies. In fact, the sequestration of carbon dioxide emissions from methane technologies would offset the currently perceived advantage of carbon-free energy sources with respect to climate change. As mentioned, carbon can be sequestered from natural gas power plants either by direct scrubbing from flue gases or through the introduction of advanced technologies such as turbines using carbon dioxide as a working fluid. The former "add-on" technology is being used today as a source of carbon (e.g., for food packaging), but it is very expensive and cumbersome for sequestration of large quantities of carbon. Assuming that future cumulative natural gas use would be in the range of the "methane age" and SRES-MESSAGE-A1G scenarios implies sequestering some 1,400 GtC during the 21st century. This is twice the current atmospheric carbon content of some 750 GtC.

One possible way of both increasing the share of methane in global energy and hydrogen-to-carbon ratio is carbon removal and disposal. Carbon removal from advanced power plants would lead to a carbon-free source of electricity, but this needs to be complemented with other liquid or gaseous carbon-free energy carriers derived from methane. Here hydrogen is an ideal candidate. For example, methane could be separated into carbon dioxide and hydrogen in the proximity of the production site. This would require the development of large-scale steam reforming processes but it is conceivable that the separation could be achieved economically. The separated carbon dioxide could be reinjected into the depleted natural gas field or used for enhanced oil recovery and hydrogen could be piped like methane. Marchetti (1992) made just such a proposal for Russian natural gas and hydrogen delivery to Europe and the use of separated carbon dioxide for enhanced oil production, for example, in the Ukraine. Initially, hydrogen could be added to the natural gas in the same pipeline and if required separated at consumption sites by membranes or other methods or simply used as a mixture of methane and hydrogen.

As the quantities of separated carbon and hydrogen from methane increase it might become necessary to build dedicated hydrogen and carbon dioxide pipelines. In the first stages of the hydrogen economy of the distant future, separated carbon might have to be deposited in the deep ocean as the fluxes become too difficult to be absorbed by declining oil production needs. Eventually, methane might be replaced as the source of hydrogen by carbon-free options. However, given the vast quantities of methane from hydrates, this does not appear to be an absolute necessity. In any case, hydrogen and electricity would provide virtually pollution-free and environmentally benign energy carriers. To the extent that they might be produced from methane, the separated carbon would be contained through storage. Once methane technologies start providing most of the energy the cumulative storage capacities would be on the order of 1,000 GtC and more requiring consideration of fundamentally different disposal options.

Marchetti (1977) proposed that the separated carbon dioxide be stored in the deep ocean through a “gigamixer” technology. This would involve injecting carbon dioxide into sinking thermohaline currents that eventually reach the deep ocean where the carbon dioxide enriched water might reside for thousands of years owing to the slow rate of natural mixing. The potential for carbon disposal in the deep ocean is vast. The global carbon cycle involves the annual exchange of around 200 GtC between oceans, the atmosphere and the biosphere. The ocean already stores on the order of 40,000 GtC.

The original proposal by Marchetti (1977) involved the Gibraltar subduction undercurrent that would provide a storage capacity of 10 GtC per year, sufficiently large to serve as a depository for all energy-related sources of carbon dioxide generated in the “methane age” scenario during the next half a century. In a more practical scheme, carbon dioxide collected in continental Europe could be transported by pipeline for disposal at Gibraltar. The theoretical mitigation potential of this scheme is vast since there are other sinking thermohaline currents including the subduction currents of Bab-al-Mandab in the Red Sea, the Weddell Sea, and the North Atlantic. This strategy could work as long as the global “conveyor belt” of ocean currents and subduction currents is unchanged, but some climate scientists are starting to challenge this assumption for anthropogenically induced climate change.

Various other disposal schemes have been proposed in the meantime: to pump carbon dioxide through high-pressure pipes to the ocean floor, to inject liquid carbon dioxide at depths of about 3,000 m that would then continue to sink, to release solid carbon dioxide (ice) that would sink by itself to the bottom, to diffuse carbon dioxide at depths of a few hundred meters leading to spontaneous formation of clathrates that would sink to the ocean bottom and to disperse carbon dioxide into a suitable thermohaline current that would carry it to the ocean bottom.

Clearly, all of these different schemes for storing carbon dioxide in either liquid or solid pools on the ocean floor or dissolved in the deep ocean still require concept proof before even a pilot project could be started. In any case, among the major outstanding uncertainties are the possible ecological effects of higher concentrations of carbon dioxide in the oceans and their effects on local chemistry in the vicinity of storage sites.

The storage of carbon dioxide in clathrates might be attractive in combination with the extraction of methane from hydrate deposits under the ocean. Methane could be extracted on off-shore platforms to generate electricity as discussed above and, in addition, to produce hydrogen. Carbon dioxide from both conversion processes could be stored in clathrates in the same deposits from which methane has been extracted. Such systems would provide both hydrogen and electricity, paving the way for a pollution-free hydrogen and electricity economy of the distant future. Electricity, hydrogen and other infrastructures (e.g. terrestrial communication networks) could be co-located, extending over whole continents and connecting the vast methane hydrate deposits with consumption centers. There, clean hydrogen and electricity technologies could provide all required energy services. Hydrogen could be used in turbines, fuel cells or catalytic burners to provide a whole range of mobile power requirements, electricity and heat. As methane contribution to global energy needs saturates and subsequently proceeds to decline, carbon-free sources of energy would take over eliminating the need for carbon handling and storage

The “methane age” scenario with carbon removal offers the opportunity for achieving global energy decarbonization and eventually eliminating carbon emissions altogether. Thus, methane fulfills most of the obvious future requirements for becoming the major source of energy. A bonus is that the reliance on natural gas can pave the way for a very clean hydrogen future.

Burning hydrogen derived from methane yields a net energy of 370.4 kJ for each mole of dissociated methane. This is a factor of 2.5 less than the energy derived from burning methane to carbon dioxide and water. Thus, an energy penalty of 520 kJ per mole of methane must be paid to prevent carbon dioxide from reaching the atmosphere (MacDonald, 1998). This might appear to be a high energy penalty from current perspectives, but with abundant methane from hydrates, hydrogen and electricity as the main energy carriers become a real possibility.

Conclusion

The findings in this study confirm that energy gases could become the means to reduce energy-related emissions of greenhouse gases and to provide affordable and sufficient energy services for further development in the world. The issue of climate warming is likely to be a major planetary concern during the 21st century, along with the need to provide sufficient energy for further social and economic development. Methane, and later hydrogen, offer one possibility for reconciling these conflicting objectives. The findings show that the evolutionary development of the global energy system towards a larger contribution of natural gas is consistent with the dynamics of the past and some scenarios of future developments. Continuation of this historical process into the future leads to carbon dioxide and methane emissions that are low compared with other, more conventional scenarios. The reasons for the moderate emissions associated with the emergence of the "methane age" are that natural gas emits less carbon dioxide than other fossil fuels and that the scenario assumes contributions of carbon-free sources of energy. These could develop under the wing of gas and become major sources of energy by 2100 and beyond.

The current phase of development of the global energy system may be just midway through the hydrocarbon era. Decarbonization in the world can continue as methane becomes the major energy source. From this perspective, methane is a transitional hydrocarbon. The great energy breakthrough that we must work for during the next decades is the production of hydrogen without hydrocarbon sources of energy (Ausubel *et al.*, 1988). 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. This transition to the methane age and beyond to carbon-free energy systems represents a minimum-regret option because it would also enhance the reduction of other adverse impacts of energy-use on the environment in addition to substantially reducing carbon dioxide emissions. Finally, methane resources are potentially so abundant that they could provide a lasting source of hydrogen and electricity, thereby achieving decarbonization of energy with carbon sequestration and permanent storage. The age of gas is a prerequisite for a carbon-free future but it also holds the promise of extending the reliance on methane well beyond the time horizon of the energy scenarios.

References

Abele, A.R. *et al.,* 1987: *An experimental program to test the feasibility of obtaining normal performance from combustors using oxygen and recycled gas instead of air.* ANL/CNSV-TM-204, Argonne National Laboratory, Argonne, USA.

Adelman M.A., and M.C. Lynch, 1997: Fixed view of resource limits creates undue pessimism. *Oil and Gas Journal*, **April**, 56-60.

Allardt, E., 1993: Having, loving, being: an alternative to the Swedish model of welfare research. In: Nussbaum, M., A.K. Sen, (eds.), 1993: *The Quality of Life.* Clarendon Press, Oxford, pp. 88-94.

Andersen, E.S., 1994: *Evolutionary economics: Post-Schumpeterian contributions.* Pinter, London, UK.

Arrow, K., 1962: The economic implications of learning by doing. *Review of Economic Studies*, **29**, 155-173.

Arthur, W.B., 1989: Competing technologies, increasing returns, and lock-in by historical events. *The Economic Journal*, **99**, 116-131.

Arthur, W.B., 1994: *Increasing returns and path dependence in the economy.* Michigan University Press, Ann Arbor, MI, USA.

Ausubel, J.H., A. Grübler, and N. Nakićenović, 1988: Carbon dioxide emissions in a methane economy. *Climatic Change,* **12**, 245-263.

Azar, C., 1996: *Technological change and the long-run cost of reducing CO_2 emissions.* Working Paper 96/84/EPS, INSEAD Centre for the Management of Environmental Resources, Fontainebleau, France.

Bajura, R.A., and H.A. Webb, 1991: The marriage of gas turbines and coal. *Mechanical Engineering Journal*, September.

Baku Pages, 2000: http://www.bakupages.com/wwwroot/fire_temple.asp.

Bolland, O. and S. Saether, 1992: New concepts for natural gas fired power plants which simplify the recovery of carbondioxide. First International Conference on Carbon Dioxide Removal, Amsterdam, March 1992. *Energy Conversion and Management,* 33(5-8),467-476.

Brantly, J.E., 1971: *History of oil well drilling*. Gulf Publishing Company, Houston, TX, USA.

BGR (Bundesanstalt für Geowissenschaften und Rohstoffe), 1995: *Reserven, Ressourcen und Verfügbarkeit von Energierohstoffen*. Stuttgart, Hannover, Germany.

BGR (Bundesanstalt für Geowissenschaften und Rohstoffe), 1998: *Reserven, Ressourcen und Verfügbarkeit von Energierohstoffen*. Stuttgart, Hannover, Germany.

BP (British Petroleum), 1996: *Statistical Review of World Energy*, British Petroleum Co. p.l.c., London, UK.

BP (British Petroleum), 1997: *Statistical Review of World Energy*, British Petroleum Co. p.l.c., London, UK.

BP (British Petroleum), 1998: *Statistical Review of World Energy*, British Petroleum Co. p.l.c., London, UK.

Campbell, J., 1959: *The Masks of God: Mythology, 1-4*. Arkana, Penguin Group, New York, NY, USA.

CEDIGAZ (Centre International d'Information sur le Gaz Naturel et tous Hydrocarbures Gazeux), 1998: *Natural gas in the world, 1998 Survey*. Rueil Malmaison, France.

Chapman, J.N., and N.R. Johanson, 1991: MHD generators in power production. *Mechanical Engineering Journal*, September.

Collet, T.S., 1993: Natural gas production from arctic gas hydrates. *US Geol. Surv.*, **65**, 299-311.

Collet, T.S., and V.A. Kuuskraa, 1998: Hydrates contain vast store of world gas resources. *Oil & Gas Journal,* 11 May, **96**(19).

Davidson, R.M., 1995: *Coalbed methane extraction.* IEA Coal Research, January, London, UK.

Energy Charter, 1998: *Energy Transit, the Multilateral Challenge,* Energy Charter Secretariat, Brussels, Belgium.

Dore, J., and R. de Bauw, 1996: *The energy charter treaty: origins, aims and prospects.* Royal Institute of International Affairs, London, UK.

Dosi, G.C., 1988: The nature of the innovation process. In: *Technical Change and Economic Theory*. Dosi, G.C., C. Freeman, R. Nelson, G. Silverberg, and L. Soete, (eds.). Pinter, London/New York, NY, USA.

Dosi, G.C., K. Pavitt, and L. Soete, 1990: *The economics of technical change and international trade*. Harvester Wheatsheaf, London, UK.

Douglas, M., D. Gasper, S. Ney, and M. Thompson, 1998: Human needs and wants. In Rayner, S. and E. L. Malone (eds.), 1998: *Human Choice and Climate Change*. **1**(3), 195-263. The Societal Framework, Battelle Press, Columbus, OH, USA.

Elvidge, C.D., K.E. Baugh, E.A. Kihn, H.W. Kroehl, E.R. Davis, *et al.*, 1997: Relation between satellite observed visible - near infrared emissions, population, and energy consumption. *International Journal of Remote Sensing,* **18**, 1373-1379.

Elvidge, C.D., K.E. Baugh, J.B. Dietz, T. Bland, P.C. Sutton, and H.W. Kroehl, 1999: Radiance calibration of DMSP-OLS low-light imaging data of human settlements. *Remote Sensing of Environment,* **68**, 77-88.

Elrod, J.P., 1997: Horizontal air drilling increases gas recovery in depleted zone. *Oil & Gas Journal,* **95**(26), 49-63.

Financial Times, 1997: Power generation equipment, 19 June, pg. VI.

Foray, D., and A. Grübler, 1990: Morphological analysis, diffusion and lock-out of technologies: Ferrous casting in France and Germany. *Research Policy*, **19**(6).

Gaz de France, 1970: Si le gaz naturel m'était conté. *GdF Informations*, (250), January, GdF, Paris, France.

Gaz de France, 1971: Si le gaz naturel m'était conté, (2éme partie). *GdF Informations*, (262), January, GdF, Paris, France.

Gold, T., 1999: *The deep hot biosphere*. Copernicus, New York, NY, USA.

Goulder, L.H., and K. Mathai, 1998: *Optimal CO_2 abatement in the presence of induced technological change*. WP 6494, National Bureau of Economic Research (NBER), Cambridge, MA, USA.

Gregory, K., and H.-H. Rogner, 1998: Energy resources and conversion technologies for the 21st century. *Mitigation and Adaptation Strategies for Global Change*, **3**(2-4), 171-229.

Gritsevskyi, A., and N. Nakićenović, 2000: Modeling uncertainty of induced technological change. *Energy Policy, forcoming.* Paper presented at the International Workshop on "Induced Technological Change and the Environment", 21-22 June, 1999, International Institute for Applied Systems Analysis (IIASA), Laxenburg, Austria.

Grossman, G., and E. Helpman, 1991: *Innovation and growth in the global economy*. The MIT Press, Cambridge, MA, USA.

Grossman, G.M., and E. Helpman, 1993: *Endogenous innovation in the theory of growth*. WP 4527, National Bureau of Economic Research (NBER), Cambridge, MA, USA.

Grübler, A., 1998: *Technology and global change*. Cambridge University Press, Cambridge, UK.

Grübler, A., and S. Messner, 1996: Technological uncertainty. In: Nakićenović, N., W.D. Nordhaus, R. Richels, and F. Tóth, (eds.). 1996: *Climate Change: Integrating Science, Economics and Policy*, *CP-96-1*, International Institute for Applied Systems Analysis (IIASA), Laxenburg, Austria.

Grübler, A., and N. Nakićenović, 1988: The dynamic evolution of methane technologie*s*. In: Lee, T. H., H. R. Linden, D. A. Dreyfus, and T. Vasko (eds.), 1988: *The methane age*,. Kluwer Academic Publishers, Dordrecht, the Netherlands.

Grübler, A., and N. Nakićenović, 1991: Long waves, technology diffusion, and substitution. *Review*, **14**(2), 313-342.

IGU (International Gas Union), 1997: *World Gas Prospects, Strategies and Economics*. Proceedings of the 20th World Gas Conference, Copenhagen.
(http://www.wgc.org/proceedings).

Ivanhoe L.F., and G.G. Leckie, 1993: Global oil, gas fields, sizes tallied, analyzed. *Oil and Gas Journal*, **91**(7), 87-91.

Jericha, H., W. Sanz, J. Woisetschläger, and M. Fesharaki, 1995: *CO_2 – Retention Capability of CH_4/O_2-Fired Graz Cycle.* Presented at the 21st International Congress on Combustion Engines, International Council on Combustion Engines, Interlaken, Switzerland.

Jericha, H., 1998: Private Communication.

Kvenvolden, K.A., 1988: Methane hydrate: A major reservoir of carbon in the shallow geosphere? *Chemical Geology*, **71**, 41-51.

Kvenvolden, K. A., 1998: *Estimate of the Methane Content of Worldwide Gas-Hydrate Deposits*, The International Symposium on Methane Hydrates, Resources for the Future? October 20-22, Japan National Oil Corporation, Chiba City, Japan.

Landes, D.S., 1969: *The unbound Prometheus: Technological change and industrial development in Western Europe from 1750 to the present.* Cambridge University Press, Cambridge, UK.

Lane, D., and R. Maxfield, 1995: *Foresight, complexity and strategy*. Santa Fe Institute, New Mexico, USA.

Law, B. E. and C. W. Spencer, 1993: Gas in Tight Reservoirs – An Emerging Major Source of Energy. In: The Future of Energy Gases. US Geological Survey Professional Paper 1570:233-252.

MacDonald, G.J., 1989: The near- and far-term technologies, uses and future of natural gas. In: *Energy Technologies for reducing emissions of greenhouse gases*, Proceedings of an experts' seminar, 12-14 April 1989, pp. 509-536, OECD, Paris, France.

MacDonald, G.J., 1990a: The future of methane as an energy resource, *Annual Review of Energy*, **15**, 53-83.

MacDonald, G.J., 1990b: Role of methan clathrates in past and future. *Climate Change*, **16**, 247-281.

MacDonald, G.J., 1998*: Methane hydrates as an energy source and a factor in climate change*. Paper presented at CRIEPI, 14 April, 1998, Tokyo, Japan.

Marchetti, C., 1977: On geoengineering and the CO_2 problem. *Climatic Change*, **1**, 59-68.

Marchetti, C., 1980: Society as a learning system: Discovery, invention and innovation cycles revisited. *Technological Forecasting & Social Change*, **18**, 267-282.

Marchetti, C., 1985: Nuclear plants and nuclear niches: on the generaton of nuclear energy during the last twenty years. *Nucl. Sci. Engng.*, **90**, 521-526.

Marchetti, C., 1992: Nuclear energy and its future. *Perspectives in Energy*, **2**, 19-34.

Marchetti, C., and N. Nakićenović, 1979: The dynamics of energy systems and the logistic substitution model. *RR-79-13*, International Institute for Applied Systems Analysis, (IIASA) Laxenburg, Austria. Also published in *IIASA Reports*, **1**(1), January-March 1980.

Marland, G., R.J. Andres, and T.A. Boden, 1994: Global, regional, and national CO_2 emissions. In: *Trends '93: A Compendium of Data on Global Change,* Boden, T.A., D.P. Kaiser, R.J. Sepanski, and F.W. Stoss (eds.). Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, ORNL/CDIAC-**65**, 505-584.Oak Ridge, TN, USA.

Marsden, S., 1993: A survey of natural gas dissolved in brine. *US Geol. Surv.*, **65**, 383-387.

Maslow, A., 1954: *Motivation and personality*. Harper and Row, New York, NY, USA.

Masters, C.D. *et al.*, 1994: *World petroleum assessment and analysis*. Proceedings of the 14th World Petroleum Congress, Stavanger, Norway.

Max, M.D., R.E. Pellanbarg, and B.G. Hurdle, 1997: *Methane hydrate, a special clathrate: Its attributes and potential*. Report No. NRL/MR/6101—97-7926, Naval Research Laboratory, 28 February.

McKelvey, V.E., 1972: Mineral resource estimates and public policy. *Am. Sci.*, **60**, 32-40.

Mendeleev, D., 1877: L'origine du pétrole. *Revue Scientifique*, 2e Serie, 7e Annee, **18**, 409-416.

Messner, S., 1997: Endogenized technological learning in an energy systems model. *Journal of Evolutionary Economics*, **7**, 291-313.

Messner, S. *et al*., 1996: A stochastic version of the dynamic linear programming model MESSAGE III. *Energy*, *the International Journal,* **21**(9).

Morita, T., and H.-C. Lee, 1998: Appendix to emissions scenarios database and review of scenarios. *Mitigation and Adaptation Strategies for Global Change*, **3**(2-4), 121-131.

Nakićenović, N. (ed.), 1993: Long-term strategies for mitigating global warming. *Energy, the International Journal,* **18**(5), 400-609.

Nakićenović, N., 1996: Freeing energy from carbon, *Daedalus*, **125**(3), 95-112.

Nakićenović, N., A. Grübler, H. Ishitani, T. Johansson, G. Marland, *et al*., 1996: Energy Primer. In: Watson, R., M.C. Zinyowera, and R. Moss (eds.), 1996: *Climate Change 1995. Impacts, Adaptations and Mitigation of Climate Change: Scientific Analyses.* Contribution of Working Group II to the Second Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, UK.

Nakićenović, N., A. Grübler and A. McDonald (eds.), 1998a: *Global Energy Perspectives*, Cambridge University Press, Cambridge, UK.

Nakićenović, N., N. Victor, and T. Morita, 1998b. Emissions Scenarios Database and Review of Scenarios, *Mitigation and Adaptation Strategies for Global Change* **3**(2-4), 95-120.

Nakićenović, N., J. Alcamo, G. Davis, B. de Vries, J. Fenhann, *et al*., 2000a: *Special Report on Emissions Scenarios*, A Special Report of Working Group III of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, UK.

Nakićenović, N., Zhou Fengqi, T. Kram, A. Makarov, B. Sørensen, *et al*., 2000b: Energy scenarios. In: Goldemberg, J. (ed.), 2000: *World Energy Assessment Report*. UNDP, UNDESA, WEC, New York, NY, USA, *forthcoming*.

Nelson, R.R., and S.G. Winter, 1982: *An evolutionary theory of economic change*. Harvard University Press, Cambridge, MA, USA.

OECD (Organization for Economic Co-operation and Development), 1996: *Energy policies of OECD countries: 1996 Review*. OECD, Paris, France.

OECD, (**Organization for Economic Co-operation and Development**) 1998: *Twentyfirst Century Technologies: Promise and Perils of a Dynamic Future.* OECD, Paris, France.

PCAST (President's Committee of Advisors on Science and Technology), Panel on Federal Energy R&D, 1997: *Federal energy research and development for the challenges of the twenty-first century*. Executive Office of the President of the United States, Washington, DC, USA. September.

PCAST (President's Committee of Advisors on Science and Technology), Panel on International Cooperation in Energy Research, Development, Demonstration, and Deployment, 1999: *Powerful partnerships: The federal role in international cooperation on energy innovation*, Executive Office of the President of the United States, Washington, DC, USA. June.

Penner, S.S. *et al.*, 1995: Commercialization of fuel cells. *Energy, the International Journal,* **20**(5), 331-470.

Revue de l'Energie, 1984: *La gaz naturel: Ressources et perspectives*, **366**, August-September 1984, Paris, France.

Rice, D.R., B.E. Law. and J.L. Clayton, 1993: Coalbed gas – an undeveloped resource. In: *The Future of Energy Gases.* U.S. Geological Survey Professional Paper 1570, 389-404.

Rogner, H.-H., 1996: An assessment of world hydrocarbon resources. *WP-96-56*, International Institute for Applied Systems Analysis (IIASA), Laxenburg, Austria.

Rogner, H.-H., 1997: An assessment of world hydrocarbon resources. *Annual Review of Energy and the Environment*, **22**, 217-262.

Rogner, H.-H., B. Fritz, M. Cabrera, A. Faaij, M. Giroux, *et al.*, 2000: Energy resources. In: Goldemberg, J. (ed.), 2000: *World Energy Assessment Report.* UNDP, UNDESA, WEC, New York, NY, USA, *forthcoming*.

Roehrl, R.A., and K. Riahi, 2000: Technology dynamics and greenhouse gas emissions mitigation – a cost assessment. *Technological Forecasting & Social Change*, **63**(2-3), 231-262.

Rosenberg, N., 1982: *Inside the black box: Technology and economics.* Cambridge University Press, Cambridge, UK.

Rosenberg, N., 1994: *Exploring the black box: Technology, economics and history*. Cambridge University Press, Cambridge, UK.

Rosenberg, N., 1997: Economic development and the transfer of technology: some historical perspectives. In: Reynolds, T. S., S. H. Cutcliffe, (eds.), 1997: *Technology and the West,* University Press, Chicago, IL, pp. 251-276.

Rostow, W.W., 1990: *The stages of economic growth*. Third Edition. Cambridge University Press, Cambridge, UK.

Schollenberger, W.E., 1998: Gedanken über die Kohlenwasserstoffereserven der Erde: Wie lange können sie vorhalten? In: Zeemann, J. (ed.), 1998: *Energievorräte und mineralische Rohstoffe: Wie lange noch?* Austrian Academy of Sciences, Vienna, pp. 75-126.

Schurr, S.H., and B.C. Netschert, 1960: *Energy in the American economy, 1850-1975*. The Johns Hopkins Press, Baltimore, MD, USA.

Shell, 1996: *The evolution of the word's energy system*. Shell International Ltd. External Affairs, Shell Centre, Londdon, UK.

Silverberg, G., 1988: Modelling economic dynamics and technical change: Mathematical approaches to self-organisation and evolution. In Dosi, G.C., C. Freeman, R. Nelson, G. Silverberg, L. Soete, (eds.), 1988: *Technical Change and Economic Theory*. Pinter, London/ New York, NY, pp. 531-559.

Smith N.J., and G.H. Robinson, 1997: Technology pushes reserves "crunch" date back in time. *Oil and Gas Journal*, **April 7**, 43-50.

Strang, V., 1997: Cultural theory and modelling practice. In: *Energy Modelling: Beyond Economics and Technology*. Giovannini, B., A. Baranzini (eds.). International Academy of the Environment, Geneva, and the Centre for Energy Studies of the University of Geneva, Geneva, pp. 53-70.

Valenti, M., 1991: Combined cycle plants: Burning cleaner and saving fuel. *Mechanical Engineering Journal*, September.

Wallace, D., 1995: *Environmental policy and industrial innovation: Strategies in Europe, the USA, and Japan.* Earthscan, London, UK.

Watson, R., M.C. Zinyowera, and R. Moss (eds.), 1996: *Climate Change 1995. Impacts, Adaptations and Mitigation of Climate Change: Scientific Analyses.* Contribution of Working Group II to the Second Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, UK.

WEC (World Energy Council), 1993: *Energy for tomorrow's world: The realities, the real options and the agenda for achievements*. Kogan Page, London, UK.

WEC (World Energy Council), 1998: *Survey of energy resources 1998*. WEC, London, UK.

Wilhite, H., 1997: Framing the socio-cultural context for analyzing energy consumption. In: *Energy Modelling: Beyond Economics and Technology*. Giovannini, B., A. Baranzini (eds.). International Academy of the Environment, Geneva, and the Centre for Energy Studies of the University of Geneva, Geneva, pp. 35-52.

Williams, R.H., B. Gunter, S. Consonni, C. Hendriks, M. van der Burgt, *et al*., 2000: Advanced energy supply technologies. In: Goldemberg, J. (ed.), 2000: *World Energy Assessment Report*. UNDP, UNDESA, WEC, New York, NY, USA, *forthcoming*.