Methane as an energy source for the 21st century

Nebojša Nakićenović

International Institute for Applied Systems Analysis (IIASA),
Schlossplatz 1, A-2361 Laxenburg, Austria
Fax: (0043) 2236-807-488 E-mail: naki@iiasa.ac.at

Abstract: Today, fossil fuels supply about 80% of global primary energy. The consequences are severe for human health from indoor and regional air pollution, acidification due to sulphur and nitrogen oxide emissions and climate change due to rapidly growing greenhouse gas emissions. Therefore, there is a clear need to improve the efficiency and the environmental compatibility of fossil technologies, shift to fossil energy sources with lower environmental impacts such as natural gas, or shift away from fossil energy use to renewable sources and nuclear power. This is an especially challenging prospect for the rapidly developing countries of Asia. Wider use of natural gas and electricity in Asia would help promote higher energy efficiencies, better quality of energy services and substantially lower environmental impacts especially at the level of energy end use. Such a transition would require new continental-scale infrastructures including natural gas and electricity grids and distribution systems.

Keywords: Natural gas; methane; combined-cycle turbines; gas turbines; decarbonisation; natural gas reserves and resources; methane hydrates; climate change; energy scenarios.

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Biographical notes: Dr. Nakićenović is Project Leader of the Transitions to New Technologies (TNT) Project at the International Institute for Applied Systems Analysis (IIASA). He is also the Convening Lead Author of the Special Report on Emissions Scenarios by the Intergovernmental Panel on Climate Change (IPCC), Guest Professor at the Technical University of Graz, an Associate Editor of the International Journal on Technological Forecasting and Social Change and of the International Journal on Energy. He holds bachelors and masters degrees in economics and computer science from Princeton University and the University of Vienna, where he also completed his PhD. Additional information can be found in Marquis Who's Who in Science and Engineering and Who's Who in the World.

This paper is based on a more extensive study conducted jointly by IIASA and International Gas Union (IGU) on *Global Natural Gas Perspectives* [1], an earlier version presented at the 21st World Gas Conference, organised by IGU, 6-9 June 2000, Nice, France and a substantially revised version presented at the Special Natural Gas Event during the 6th conference of the Parties of the United Nations Framework Convention on Climate Change, 1 November 2000, Hague, The Netherlands.

1 Introduction

The provision of adequate and affordable energy services is a prerequisite for further social and economic development in the world. This is a formidable challenge for the 21st century. It is estimated that at present about two billion people do not have access to commercial energy [2]. At the same time, median demographic projections indicate that global population will increase by four billion to ten billion during the 21st century. This means that about six billion people would need to be 'connected' to the global energy system during the 21st century, a number equivalent to the current global population.

The provision of these additional energy services is unlikely to be possible with the current structure of energy system and technologies: already today the adverse impacts associated with energy pose severe environmental and health threats ranging from indoor air pollution and regional acidification to climate change. A transition to the efficient and environmentally benign provision of an energy service could avert in the future the potential conflict between development and protection of the environment. This is an especially challenging prospect for the rapidly developing countries of Asia. The development of new continental-scale infrastructures for clean energy will be required in order to harmonise the ever-greater needs for affordable energy services with the potentially severe adverse environmental impacts of energy systems. In particular, new natural gas and electricity grids and distribution systems for Asia are needed [1].

Infrastructures are the backbone of future economic and social development. They serve as 'catalysts' for the diffusion of new forms of human activities and diffusion of new technologies. Transport, communication and energy infrastructures are of particular importance in this context. They can be seen as essential prerequisites for future development. Yet they require large and dedicated investments in individual links and connections well before whole systems and networks of infrastructures can emerge on continental scales. Often, such investments are too 'lumpy' to be raised on private capital markets and associated risks are usually quite high. Therefore, the development of infrastructures requires long-term vision and readiness to accept initially low returns on investment in exchange for more rapid economic and social development in the long run.

In conjunction with new and advanced technologies, methane and other energy gases can provide a large part of the rapidly growing need for clean and affordable energy services in Asia [1]. These opportunities offered by methane technologies are enhanced by increasing evidence of methane resource abundance in the world by the three pervasive historical processes of change: the trend toward the pervasive decarbonisation of energy in the world, striving for higher energy efficiencies and increasing competitiveness of methane technologies through declining capital investment requirements. These opportunities offered by methane technologies can be realised in currently developing parts of the world and Asia in particular, only if appropriate energy transport infrastructures are in place during the coming decades. These could pave the way for a more prosperous future with less human intrusion on nature and interference with planetary processes such as climate change.

2 Gas turbines and other methane technologies

The conversion of natural gas into electricity, mechanical energy and heat is very efficient in comparison to other hydrocarbon fuels. At the same time, electricity from natural gas is more competitive than other options where transport and distribution infrastructures exist. In fact, it is usually the cheapest and preferred source of electricity. The capital costs of natural gas power plants are much lower compared to other options. This is an important competitive edge in privatised and deregulated energy markets.

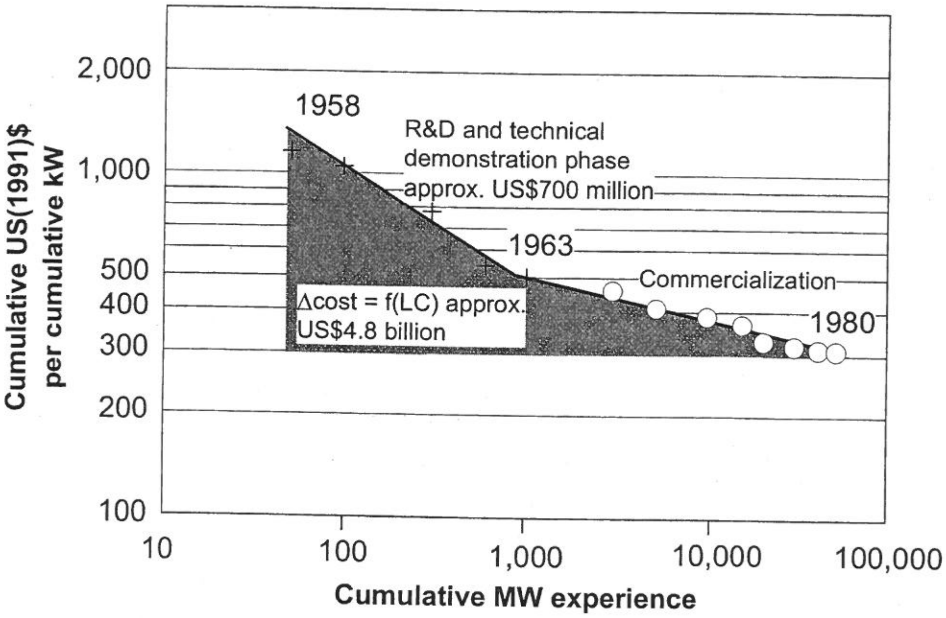
The last two decades have seen the dramatic breakthrough of combined-cycle gas turbines (CCGTs). This technology involves expanding very hot combustion gases through a gas turbine with the waste heat in the exhaust gases used to raise steam for a steam turbine. The gas turbine can withstand much higher 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%. What is also impressive is that this figure has been rising by over 1% per year for over a decade. The low capital costs and high availability of combined-cycle turbines also make them highly desirable to power station operators. Gregory and Rogner [3] estimate that efficiencies of 71% to 73% are achievable within a reasonable period (on a lower heating basis, around 65% to 68% on a higher heating basis).

In contrast, a century ago the first power plants using steam engines for generating power resulted in overall conversion efficiencies of some 5%. 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 represents a factor 12 increase in conversion efficiency during the 20th century, corresponding to an improvement rate of about 2.5% 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 a hundred 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. This has been the result of the vigorous technological change of gas turbines and other associated systems. Technological change increased the performance of energy conversion, decreased their costs and at the same time reduced environmental impacts at all scales. Environmental and economic concerns have also led to major technological development programs directed towards improving efficiency and reducing costs and emissions.

The impressive cost reductions of natural gas turbines for electricity production can be illustrated 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 1 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 led to early commercialisation 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 a profit-making 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 original investments 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). It illustrates that the impressive improvements in gas turbines were not 'autonomous' but rather that they were the result of dedicated research and development programs and steady market introduction. Today, gas turbines constitute some 40% of all electric power plants in the world.

Figure 1 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. The shaded area indicates the cumulative investments estimated for research and demonstration phase (US$700 million) and those estimated for achieving commercialisation (US$4.8 billion) of gas turbines



Current technological development of gas turbines primarily includes further improvements to combined-cycle schemes. At the same time, environmental considerations often require the addition of flue-gas clean-up 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. 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 [4]. Further efficiency improvements of a few percentage points are expected in the next years for combined-cycles. The emissions of such plants are already generally very low compared to conventional coal and oil power plants, 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 oxide emissions significantly [5].

Another new technology for the conversion of natural gas into electricity is the magneto-hydrodynamic (MHD) generator. Instead of a rotating metallic conductor as used in conventional mechanical-electric generators, the 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 ionised gas or a liquid metal. In the case of natural gas, the fluid is the ionised combustion gas [6].

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%.

All of these recent technological developments favour 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 privatised energy markets. As a result, the combined-cycle technology represents a hedge against the uncertainty of future environmental policy priorities, and represents an effective least-regret cost investment strategy associated with hydrocarbon fuels. That is, the attractiveness of combined-cycle technology does not just 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 gasification or coal-based clean fuels [7].

In general, 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 capture and storage are all options that are likely to diffuse in many parts of the world during the 21st century. For example, 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 already achieved with current gas turbines. These new technologies could make natural gas even more competitive, more reliable and even more broadly available.

Another clean fossil technology is the combustion of natural gas (or synthesis gas from coal or pulverised 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 [8]. 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% [9].

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 and eventual storage without the need for additional equipment.

There are many other possibilities for the eventual separation of carbon from methane. One of the current technologies that could be employed is steam reforming of natural gas into a stream of carbon dioxide and hydrogen. Carbon dioxide could be used for enhanced oil and gas recovery, stored in depleted natural gas fields or in aquifers close to the separation facility. Other carbon storage alternatives include ocean deposition as clathrate locked, liquid or solid carbon dioxide. The separated hydrogen could either be added to methane in the pipelines to decrease further the carbon intensity of the resulting energy gas or shipped as a carbon-free energy carrier to end use. Further versions of this technology include the use of other carbon-free energy sources such as high-temperature nuclear, wind or photovoltaics for the steam reforming process in order to maximise the utilisation of methane as a source of hydrogen.

3 Natural gas fuel cells for electricity and mobility

The major potential competitor to combined-cycle natural gas technology is the fuel cell that may offer similar efficiencies at much smaller 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 specialised 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 [10].

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%. 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 (megawatts electric), 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 fuelled with a hydrocarbon fuel such as 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, 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, fuelled by hydrogen, there are two fuel cell designs suited for clean hydrocarbon fuel utilisation. 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 utilise coal directly in the foreseeable future. In the meantime, the dominant fossil fuel cells will be fuelled 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 utilises an electrolyte consisting of molten salts operating at 650°C, opening up the possibility of using carbonaceous fuels and internal reforming. Hydrogen is immediately oxidised electrochemically to water vapour, 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% for synthesis gas and natural gas, respectively.

Solid oxide fuel cells operate at temperatures in the vicinity of about 1000°C. When fuelled 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 efficiency by about ten percentage points. The advantage of solid oxide cells is that they have a relatively high tolerance to impurities such as sulphur, 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 commercialisation needed 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.

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, new renewables and, where appropriate, nuclear power also. New technologies need to become commercially viable and attractive through better technical and environmental performance, universal availability and perhaps foremost a significant reduction in costs. This requires continued research and development efforts as well as investments in new technologies [11]. The decisive advantage of natural gas today is that the combined-cycle gas turbine is just such a technology, its performance was improved and its costs have declined dramatically during the last three decades. Continuous improvements need to be sustained for a whole host of methane and other energy technologies in the future to meet the challenge of the 21st century.

4 Methane reserves and resources

Perceptions about global methane resources have changed drastically. Methane, the main constituent of natural gas, is much more abundant around the world than was estimated just a decade ago. In general, new discoveries, including additions to reserves have by far outpaced increases in global consumption. Another important development is that some of the so-called unconventional sources are becoming competitive, such as tight gas, Devonian shares and methane extraction from coal beds. Resources of conventional and unconventional gas continue to be revised upwards. Table 1 compares historical and current hydrocarbon energy consumption with estimated reserves, resources and other less certain 'additional occurrences'.

Table 1 Global hydrocarbon consumption (cumulative and in 1998), reserves, resources, resource base (sum of reserves and resources) and more speculative occurrences, in ZJ (10^{21}J)

	Consumption		*Reserves*	*Resources*	*Resource*	*Additional*
	1860–1998	*1998*			*Base*	*Occurrences*
Oil						
Conventional	4.8	0.14	6	5	11	
Unconventional	--	--	6	12	18	> 60
Gas						
Conventional	2.3	0.08	4	8	12	
Unconventional	--	--	5	7	12	> 10
Hydrates	--	--	--	--	--	> 800
Coal	5.4	0.09	45	108	153	> 130
Total	12.5	0.31	66	140	206	> 1000

Source: [12-15]

Historical comparison indicates that about half as much methane has been consumed since the 1860s in the world compared with coal and crude oil. Coal was the first hydrocarbon energy source to be introduced with the advent of the 'steam age' to replace traditional energy uses such as firewood and working animals. The consumption of crude oil has been especially vigorous due to the rapid increase of global mobility during the last half century with the expansion of road networks and the use of the automobile. The current hydrocarbon global energy needs are about 310 exajoules (EJ) per year constituting about 80% of total energy requirements. The rest is accounted for by traditional energy uses in the developing regions, hydropower and nuclear energy.

Future prospects of securing adequate hydrocarbon reserves and resources are promising especially when compared with current energy requirements. Table 1 shows known hydrocarbon reserves, resources and so-called 'additional occurrences.' Hydrocarbon energy reserves and resources can be classified according to a two-dimensional matrix originally proposed by McKelvey [16]. 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. Reserves are those hydrocarbon deposits that are known to exist and that can be extracted with current technologies and energy prices.

Resources are less certain either because of lower geological certainty of resource occurrence, high costs of recoverability or lack of appropriate extraction. Geological certainty depends both on advances in the science of geology and on the prospecting and extraction technologies, while the economics of recoverability depend on energy prices and extraction technologies. Thus, the concept of energy resources is dynamic. Increasing energy prices, advances in geology and prospecting activities as well as technological change can lead to new discoveries and reclassification of resources into reserves. In fact, the global resources have and are expected to continue to grow faster than energy consumption. The sum of reserves and resources is collectively denoted as the 'resource base' in Table 1.

All types and forms of hydrocarbon deposits are collectively called 'occurrences.' Thus, the concept of 'additional occurrences' is even more speculative. What is considered to be a hydrocarbon occurrence has changed drastically during the last three decades since the so-called energy crisis. The most drastic change in perceptions about energy resources is associated with the vast quantities of methane trapped in ice, so-called methane hydrates or 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. Today, they are being investigated as the potentially largest speculative source of natural gas. If ever commercially exploited, they could supply any conceivable future energy demands for centuries to come, rendering methane de facto into a 'renewable' energy source. The challenge is to understand the conditions including the development of new technologies and infrastructures that would allow some of these enormous deposits to be successfully exploited in the future.

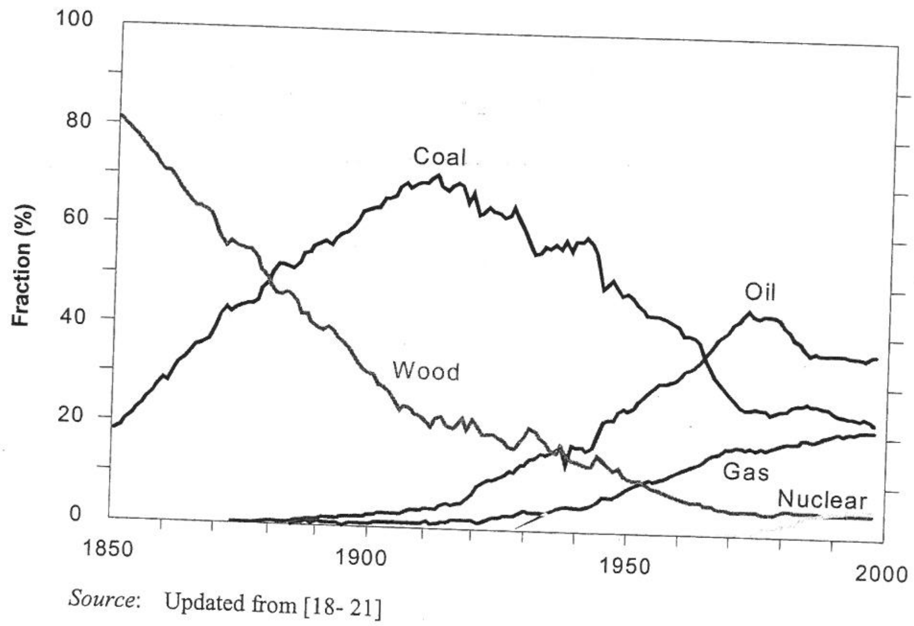
Energy reserves, resources and additional occurrences represent extremely large carbon deposits even when compared with other planetary carbon sources and flows. Current global hydrocarbon energy use results in emissions of 6 GtC (billion tons of elementary carbon) per year into the atmosphere. The historical hydrocarbon energy consumption has resulted in some 270 GtC cumulative emissions, which increased the atmospheric carbon dioxide concentrations from some 280 ppmv (parts per million volume) two hundred years ago before the onset of the 'fossil age' to 368 ppmv today. The hydrocarbon energy reserves of 66 zetajoules (ZJ) from Table 1 correspond to about 1550 GtC, an amount twice the current atmospheric carbon content. This quantity of carbon would essentially double the current atmospheric carbon content to about 750 ppmv, assuming that about half of the released carbon dioxide would remain in the atmosphere. The resources contain more than twice the carbon compared with the reserves. The hydrates represent a carbon deposit of vast proportions with some 10,000 GtC. In comparison, the largest known pool of carbon is dissolved in deep oceans and is estimated at 40,000 GtC. This illustrates quite clearly that the 'carbon endowment' of energy resources and occurrences 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. Thus, either a transition toward non-carbon sources of energy will be accomplished during the 21st century or new and advanced hydrocarbon energy technologies will be deployed for removing and storing carbon. Methane is well suited to become a source of carbon-free energy carriers both because the carbon storage requirements and removal effort would be smaller compared to coal and crude oil.

5 Energy decarbonisation

The notion of decarbonisation describes the historical transition from a carbon-intensive to less carbon-intensive energy structures. To a large extent global decarbonisation has resulted through an increasing reliance on natural gas, the least carbon-intensive of all hydrocarbon energy sources, and in recent decades to a lesser extent through the introduction of nuclear and modern renewable energy sources, which contain no carbon (see [17,18]).

Decarbonisation of energy delivered to end use is driven by the increasing need for 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 [13]. Thus, the question is whether the drive towards electricity and hydrogen-rich energy can be reconciled with the relatively slow and in some cases even opposing changes in the structure of energy systems and the primary energy supply. The historical replacement of traditional energy by coal, coal by oil, and later by natural gas is shown in Figure 2. This is a well-documented, dynamic and regular evolutionary process. It indicates future possibilities.

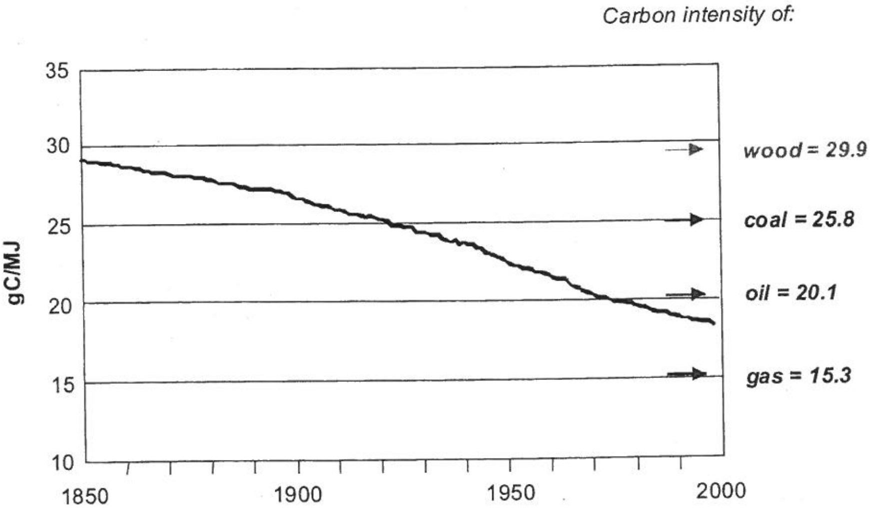
Figure 2 Global primary energy substitution, historical development from 1850 to 1990, in fractional shares, in percent



Source: Updated from [18- 21]

Assuming the same dynamics and regularity of primary energy substitution as in the past, an explorative view into the future projects methane to be the dominant source of energy during much of the 21st century, although oil should maintain the second largest share through the 2030s [22]. In the past, energy substitution has indeed resulted in a substantial decarbonisation of global energy. The unfolding of primary energy substitution in this scenario implies a gradual continuation into the future of the historical decarbonisation process shown in Figure 3. If natural gas does indeed become the dominant source of energy in the 21st century, the average carbon to energy ratio can be expected to approach the level of some 15 grams of carbon per megajoule (gC per MJ), a level that corresponds to four hydrogen to one carbon atom given by the molecular structure of methane. Improvement beyond this level would have to be achieved by the introduction of carbon-free energy sources and by carbon sequestration from hydrocarbon energy, in particular from methane.

Figure 3 Decarbonisation of energy as the ratio of carbon over global primary energy, historical development from 1860 to 1990, as a ratio of carbon dioxide emissions over energy in gC/MJ (gC 10^{-6} J^{1})



Source: Updated from [20, 13]

6 Climate change

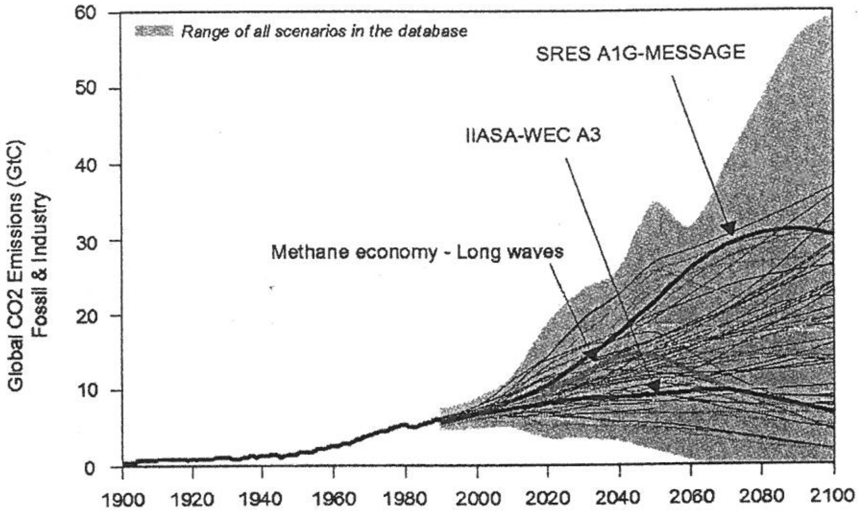
Natural gas is the cleanest of all hydrocarbon energy sources. It has very low emissions of pollutants such as particulate matter, carbon, sulphur and nitrogen oxides even with current technologies. For example, it results in less than half the carbon dioxide emissions per unit useful energy compared with coal and slightly over half per unit primary energy (see also Figure 3). It has very little, if any, sulphur as an energy carrier so that its combustion products are essentially free of sulphur 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 acceptably low emissions levels. With the diffusion of advanced technologies that involve carbon removal and storage, natural gas usage 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 oxidised during combustion of hydrocarbon fuels leading inherently to emissions of carbon dioxide. However, there are methods of sequestering carbon before combustion such as the turbines that use carbon dioxide as the working fluid (see the above discussion about advance methane technologies) and after combustion such as the carbon scrubbers. These technologies could minimise carbon dioxide emissions to the atmosphere also in conjunction with expanded use of methane as a major future energy source. This would require some form of carbon storage over millennia. Carbon dioxide clathrates could provide one of the possibilities for storing sequestered carbon in the future. Thus, the extraction of methane from clathrates might help promote the technological development required for carbon storage in the future and would provide a vast and practically inexhaustible clean energy source for the masses. Energy decarbonisation strategies favour natural gas because of its lower carbon content compared to other hydrocarbon fuels and thus lower sequestration efforts.

At the same time, natural gas consists mostly of methane, a gas with a very strong but much shorter greenhouse effect than carbon dioxide, so that avoidance of these emissions is of great importance and needs to be an essential component of energy decarbonisation strategies. However, coal and oil extraction and processing releases methane as well. Studies of the combined effect of carbon dioxide and methane emissions for natural gas-intensive scenarios in the literature indicate that the total greenhouse effect would indeed be significantly lower compared to more traditional scenarios that rely more heavily on more carbon-intensive fuels such as coal and oil (see [23]). Nevertheless, the methane leaks associated with a further increase of natural gas, oil and coal use could be significant and may increase the total greenhouse effect by about 10% in addition to the carbon dioxide emissions.

Figure 4 shows the historical increase of global carbon dioxide emissions and indicates possible future development based on the scenarios in the literature [24]. Some of the scenarios anticipate a tenfold increase of global emissions during the 21st century, a level that would be associated with a significant degree of climate change. Other scenarios that include higher shares of methane and zero-carbon options lead to an initial increase followed by an eventual decline. Scenarios denoted as the 'methane age' [22], the IIASA-WEC A3 scenario [14] and the IPCC SRES A1G scenario [24] rely on a significant contribution of methane to the global energy supply followed by the development of new renewables and nuclear energy. These methane-intensive scenarios are consistent with the stabilisation of atmospheric concentrations of carbon dioxide at twice the pre-industrial levels (at some 550 ppmv). Further reductions of the stabilisation levels would require carbon sequestration from methane and timelier penetration of zero-carbon sources than postulated in most of the scenarios in the literature.

Figure 4 Global carbon dioxide emissions, historical development from 1900 to 1990 and scenarios in the literature, in GtC (10^{12} gC) per year. Low emissions scenarios denoted as 'methane age', the IIASA-WEC A3 and SRES-A1G have high shares of methane in global energy supply followed by development of new renewables and nuclear



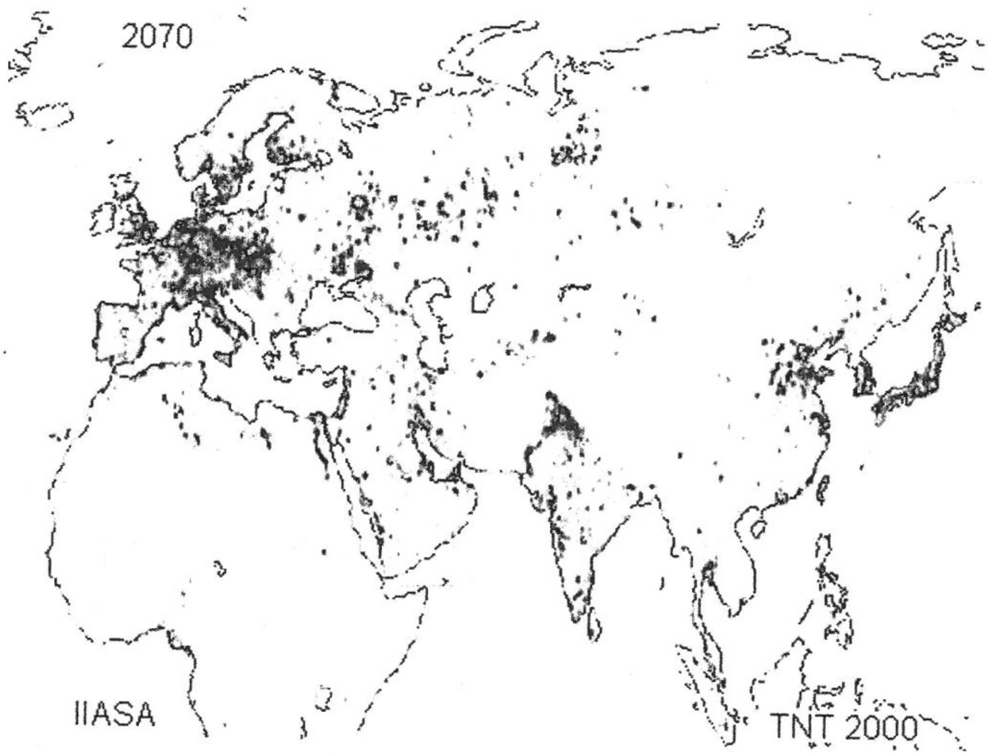
Source: [22,14,24]

7 The methane age

Climate change 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 in the world. Methane, electricity and later hydrogen offer the possibility to reconcile these conflicting objectives. The evolutionary development of the global energy system towards a larger contribution of methane is consistent with the dynamics of the past (Figure 3) and some scenarios of future developments. Continuation of this historical process in the future leads to carbon dioxide emissions that are low compared with other, more conventional scenarios of possible global energy developments (Figure 4). The reasons for the moderate emissions of the 'methane age' scenario are that natural gas emits less carbon dioxide than other hydrocarbon fuels and that it can be used to produce carbon-free energy carriers such as electricity and hydrogen. Thus, carbon-free energy could develop under the 'wing of gas' and become a major source of energy by 2100 and beyond. The current phase in the development of the global energy system may be just midway through the hydrocarbon era.

Decarbonisation in the world can continue, as methane becomes the major energy source (Figure 3). This, however, requires the development of a whole host of new methane technologies and the emergence of large-scale interconnected energy grids throughout the world and especially in Eurasia where the largest increases in energy services are expected. Figure 5 illustrates future energy needs in Eurasia based on the IPCC SRES A1G scenario [24,25]. It shows the luminosity at night as might be observed by a satellite orbiting the earth in the 2070s. Especially noticeable in this scenario are the future 'megapolis' constellations in Central Europe, Japan, China, India and Korea. Pipelines, electric grids and other transport forms are needed to connect the vast methane resources of Siberia and the Caspian with energy consumption centres in Eurasia. This would constitute an important prerequisite for the achievement of clean energy development and sufficient provision of affordable energy services in Eurasia. Further systems of pipelines might be needed for transport and storage of separated carbon.

Figure 5 Satellite-like image of night luminosity across Eurasia in 2070 for a gas-intensive SRES-A1G scenario. In addition to luminous urban areas in Europe and Japan, mega urban settlements in China and India require enormous amounts of clean energy services to be provided by future electricity and natural gas infrastructures. Incidentally, the remnants of current infrastructures are clearly seen in 70 years from such as the luminous filament across the path of the current Trans-Siberian railway. The large 'dark' patches indicate areas where more decentralised forms of clean energy services have to be provided to future residents of rural areas today mostly excluded from the access



Source: [24,26]

Such scenarios of future developments imply a drastic but essential energy-geopolitical shift. They would constitute a first step in the long-term energy transition toward cleaner and more convenient provision of energy services. Extraction of carbon-free energy carriers such as hydrogen and electricity from vast methane hydrates from oceans and permafrost regions might constitute the next important step in this transition towards sustainability in the very long run beyond the 21st century. From this perspective, methane is the transitional hydrocarbon of choice for the 21st century. The energy breakthroughs that must be achieved during the next decades are the development of new methane technologies and the production of hydrogen without hydrocarbon sources of energy.

Methane resources such as hydrates are potentially so abundant that they could provide a lasting source of hydrogen and electricity thereby achieving decarbonisation of energy with carbon sequestration and permanent storage. Thus, natural gas could be the bridge to carbon-free energy sources, such as solar or fusion energy, or hydrogen extracted from the vast clathrate resources. Decarbonisation of methane from clathrates, and other gas sources in general, will require the development of new technologies and innovative schemes for carbon sequestration and storage in the future to produce carbon-free energy gases such as hydrogen and other carriers such as electricity. This transition to the methane age and beyond towards 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 a substantial reduction of carbon dioxide emissions.

8 Conclusion

The methane age could become the principal means for reducing energy-related emissions of greenhouse gases. Methane appears to be ideally suited to be a bridge from the current energy system to a new era of environmentally sound and carbon-free energy systems beyond the 21st century. It can also help achieve two important energy goals – supplying the energy services needed for social and economic development and reducing adverse impacts on the environment at all levels. Development of clean energy infrastructures for the transport of energy gases and electricity is a prerequisite for the achievement of both of these development and environment goals.

Thus, methane holds great promise as the global energy source of choice for the 21st century and beyond. It is the cleanest of all hydrocarbon energy sources, it has high conversion efficiencies and is likely to be available for a very long time to come. Methane could help in creating an era of affordable, abundant, pervasive and clean provision of energy services throughout the world. The challenge is to develop and diffuse throughout the world the new methane technologies and new energy infrastructures required for achieving this transition.

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