TECHNOLOGY AND THE PROSPECTS FOR NATURAL GAS
Results of Current Gas Studies

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FOREWORD

The historically observed shifts in the pattern of energy supply mixes have not been the result of resource scarcity but are evolutionary adjustment processes to changing social and economic requirements. Socioeconomic adjustment processes usually collude with technical progress and fundamental technological change. To that extent the past shifts in primary energy supplies from wood to coal and eventually to oil have been technology rather than energy substitutions supporting economic structural change, such as the first industrial revolution or the penetration of chemical engineering and the automobile, respectively.

Presently, structural economic change and new sociopolitical requests for cleaner and environmentally benign forms of energy supplies demand another shift in the primary energy balance. Natural gas, or its main component methane, is well suited to meet this demand. This, and not dwindling oil resources, will be the driving force for the anticipated shift from oil to natural gas. Again, the role of technology paving the way for this transition is of the essence.

During the course of IIASA's International Gas Study, special emphasis was given to the role of technical change and its impact on future energy supply scenarios as opposed to the traditional "fixed technology projections", underlying most energy and gas analyses. This paper reports on the results of this effort.

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Technology and the prospects for natural gas

Results of current gas studies

Hans-Holger Rogner

Over recent years advances in the fields of geosciences and drilling technologies resulted in notable additions to the global hydrocarbon resource base. Similar advances occurred within the downstream parts of the energy sector. Somehow these changes have not been recognized by most energy analysts and thus are not reflected in their resource estimates or long-term energy projections. Although technology advances are not restricted to any particular area or type of fuel, there now seems to be growing evidence that most probably the balance will tilt substantially in favour of natural gas. This paper is an attempt to account for the impact of present and future technical changes on the longer term European primary energy mix.

Keywords: Natural gas; Technology; Energy scenarios

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[1]N.W. Peebles, *Prospects for Natural Gas Through to the Year 2000*, 16th World Gas Conference, IGU/TFI-85 International Gas Union, Paris, France, 1985.

[2]Usually in form of static reserve-to-production ratios or recovery rates. These ratios, however, are one time snap shots based on existing exploration and production technologies and neglect the aspects of dynamic technical change.

At the outset of his contribution to the 16th World Gas Conference M.W.H. Peebles[1] presented the sequence of distinct steps conventionally adopted for the assessment of future supply and demand for energy in general and for natural gas in particular. Typically, the assessment of the prospects for natural gas begins with the conceptualization of an overall business perspective. Since the era of predominant dependence on oil is likely to last well into the 21st century and economic performance continues to be highly sensitive to the dynamics of the international oil market, the next step defines an outlook for oil. Only then does the analysis turn to the assessment of the potential role for natural gas within the setting defined by the two preceding steps. However, one essential factor is omitted from most gas studies. Technology, though implicitly present within the numerous assumptions[2] underlying such analyses on future gas prospects, hardly enters energy projections as a variable in its own merits. Consequently, these studies disregard the impact of technical progress on the composition of future primary energy supply mixes. The delicacy of this omission will be elaborated within a comparison of the results of recent gas studies.

The business perspective

Table 1 contains a rough breakdown of the principal components of major natural gas studies. The overall business perspective serves as the background against which future energy demand and supply patterns will be assessed. Basically, this step is an attempt to identify the economic and political climate at the macro level and aims at a quantification of the dynamics and trends of those factors impinging directly or indirectly on energy demand. First of all these include future economic growth patterns, ie the volume and quality of economic activity and the effects of industrial structural change on energy intensities.

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Table 1. Components of major gas studies.

Business perspective
Industrial activity and structural change
Energy conservation, price responsiveness
Environment
Energy policy
Outlook for oil
Prices *v* supplies
Prospects for natural gas
Resource base
Interfuel competition
Gas-to-gas competition (recently)
Spot market (recently)

Second, the future potential of price-induced energy conservation must be quantified. In the wake of extended periods of low oil market prices the question of permanent *v* temporary conservation effects becomes an important issue.

Third, there is the host of government regulatory constraints and energy policies which impact on the level and mix of energy consumption. Environment oriented regulations towards reduced stack emissions change the economics and preference for individual fuels though not necessarily in a consistent way. For example, electricity at the point of consumption is highly preferable which is not always the case at the point of generation. Energy policy influences both the absolute levels of energy demand and supply as well as the composition of energy consumption. Most notably there is the dichotomy between the perceived value of domestic resources *v* the critical level of dependence on foreign supplies, particularly from politically diverse sources. Energy policy usually means interference with, and distortion of, the free interplay of market forces and may result in an unfair advantage/disadvantage for a particular fuel *v* its competitors.

The outlook for oil

The outlook for oil, ie availability and international market price of oil, has been and will continue to remain the yardstick for all other energy forms. However, in an effective market environment one would not expect any other criteria than burnertip competitiveness as the market clearing mechanism. It is the inherently long lead times required for any significant change in the demand and supply structures which preserve the dominating role of oil and sensitize energy markets.

In the recent past even minor changes in the oil business have had major destabilizing effects. There is OPEC's shift from being the world's principal supplier to a swing producer. It is the OPEC multiplier phenomenon (Mossavar-Rahmani, 1983),[3] ie the combined effects of investments dynamics within the typical business cycle and the over-reaction of virtually all agents involved in the production, transport, refining, distribution and consumption of oil, which again retain the quasi reference role of oil in current and future energy markets.

In summary, the potential for interfuel substitution of other forms of energy for oil will over and above burnertip competitiveness depend on the perceived availability and the anticipated price of oil.

Prospects for natural gas

Factors most relevant to natural gas include an appreciation of the resource base, the interfuel competition and contract/pricing issues all of which centre around the specific properties of methane. Resources are plentiful but distances between resource locations and consumption centres have been continuously increasing. This aggravates the traditional transportation disadvantage of natural gas. In addition, geopolitical concerns are being expressed whenever the large-scale use of the world's largest known gas reserves of the USSR and the Middle East is considered.

Interfuel competition for natural gas is usually restricted to stationary applications which by definition excludes the transport sector. Furthermore the decomposition of methane requires high temperature heat and thus limits its use in the feedstock market.

[3]Bijan Mossavar-Rahmani, *OPEC and the World Oil Outlook*, The Economist Intelligence Unit, Special Report No 140, EIU, London, UK, 1983.

The pricing of natural gas, to a large extent, is subject to institutional influences and policies with free market forces and competitiveness playing often no more than a marginal role.

Because of the recent surplus, gas supply capacity in major gas markets, gas-to-gas competition, or signs of a possible development of a spot market have received attention. Here, the main concern relates to the adverse effects of price cutting competition to recover some of the sunk capital on the producers' incentive to commit investments in new production capacity. Also spot sales have created some unease in an otherwise precisely 'contracted' market.

The missing element

The commonality of the approach underlying most gas studies together with the uncertainties arising from political events of the 1970s regarding security of supplies, the wide fluctuations in energy prices plus major world fuel trade and consumption distortions have led to very cautious and almost uniform energy demand projections. The modest energy demand growth expectation for the remainder of this century and the present oversupply situation have in many areas lifted the concerns with regard to energy supplies. A flamboyant demand-creates-its-own-supply attitude is prevailing in many energy related fields.

During the early 1980s when the contracted market began to break down and the long-term supply from secure sources became an issue quite a few gas studies were performed. By and large these gas studies, eg conducted by the International Gas Union, the International Energy Agency, Commission of European Communities, the Data Research Institute, the Massachusetts Institute of Technology or Harvard University adhere to the principals of economics, ie 'natural gas must be priced competitively downstream'[4] or 'the ability of the industry to bring remotely located reserves to market at the right time, in sufficient quantity, and at marketable prices which at the same time offer the supplier an acceptable economic return'[5] as the decisive criteria in their analyses. However, economics is, to a large extent, a derivative of policy and technology. Both factors are usually poorly represented.

Regarding the policy factor the pervasive influence of governments and energy policies is acknowledged ('policy is everything in an enough of everything situation') but usually kept as fixed parameters over the entire projection horizon. But government policies are subject to change, a fact disregarded by many energy/gas studies. Self-fulfilling prognosis is often the outcome of this procedure. For example, a policy that inhibits gas from being used as a fuel for electricity generation will, if maintained in an economic analysis, exclude gas from the supply mix of the electricity sector despite its potential economic viability. Planning for the future based on such intelligence might forfeit valuable market shares for natural gas.

Even more significant than constant energy policies are the consequences of constant technology energy projections. The major forces of the last decade which countered the 'running-out projections' of the Club of Rome, the perception of an inelastic energy demand or eventually the power of OPEC are, to a large extent, attributable to technology. The term technology as used in this context includes productivity and efficiency increases as well as infrastructural adjustments – in short all those elements that can be subsumed under 'technical progress or dynamics of technology'. It is intriguing that the

[4]Harvard University, *Prospects for Natural Gas Trade in North America and Western Europe: Reports of Two Executive Sessions*, Discussion Paper Series E-85-08, Harvard International Gas Study, John F. Kennedy School of Government, Cambridge, MA, USA, 1985.
[5]Peebles, *op cit*, Ref 1.

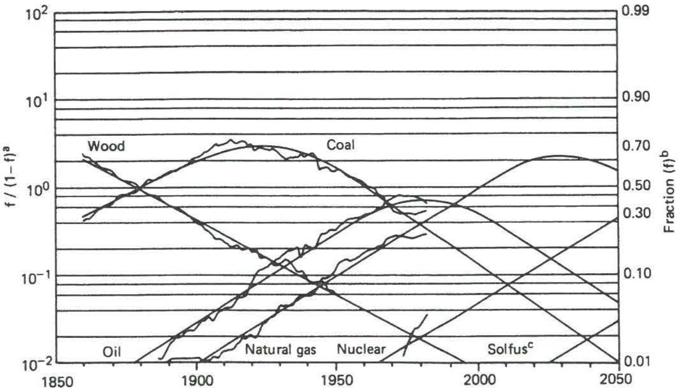

Figure 1. Global primary energy substitution.

Source: Grübler and Nakicenovic.[7]

[a]Market share of a technology or primary energy form over the market share not reached by this technology.
[b]*f* = market share.
[c]Solfus = solar and/or fusion.

evolution of technical progress has been ignored in most gas studies and their specific projections and assessments have been based on state-of-the-art technology only.[6]

Unlike energy policy, technology cannot change overnight. Invention and innovation, however, the driving forces behind technical progress and economic development, are always present though often undetectable in the short run. Hence, in a study concerned with short-term forecasts of natural gas prospects, eg gas sales for the next quarter or so, technological change will not be a critical variable, but in any study which looks 10 or more years into the future, technology may impact the market realities at the same rate as does energy policy. Although we are unable to predict the future policies, one can be assured that tomorrow's technology will differ from today's. A sound portion of understanding of the dynamics of technology is a prerequisite in any longer term energy demand and supply planning exercise. Strategic planning depends on a consistent analytical framework which at least should account for prospective technological change. Historical developments can serve, at least as zero order, guidelines when specifying assumptions for future technology evolutions.

Over the last 150 years the global energy system has experienced a number of evolutionary changes as the fuel mix shifted from the dominance of wood to coal and subsequently to oil (see Figure 1). These substitutions of one form of primary energy for another have occurred in collusion with fundamental technological change and are technology rather than energy substitutions. Furthermore, these shifts have been independent of the actual resource situation, ie the world was not running out of coal when oil began to displace coal. Even economics was not the initial driving force until an oil accommodating infrastructure was developed and the learning curve and economics of scale became effective. The reason for the success of oil increasing its market share against coal is that oil is superior to coal in many dimensions and better suited to society's needs. A least cost energy supply analysis performed at the beginning of this century would most likely have suggested that coal supply is getting into a squeeze a few decades down the road and missed the potential for oil entirely.[8]

Today we experience a situation which resembles the initial stages of the oil for coal substitution. Again oil resources are still plentiful. But society has been sensitized by the destabilizing events of the 1970s,

[6]The Gas Research Institute in its *1985 GRI Baseline Projection of US Energy Supply and Demand to 2010* for the first time included a revised technology scenario after recognizing that technological developments within GRI funded R&D programmes were in conflict with the projections in some critical areas. Another exception from this constant technology approach is an article by P. Tempest, 'Beyond the rainbow: gas in the twenty-first century', in Melvin A. Conant, ed, *The World Gas Trade: A Resource for the Future*, Westview Press, UK, 1986.

[7]Arnulf Grübler and N. Nakicenovic, *The Dynamic Evolution of Methane Technologies*, Working Paper WP-87-2, International Institute for Applied Systems Analysis, Laxenburg, Austria, 1987.

[8]'There is an old and well-justified joke that if a cost–benefit analysis had been made at the crucial time, then sail would have never given way to steam'. Jerry R. Ravetz, 'Usable knowledge, usable ignorance: incomplete science with policy implications', paper presented at the Sustainable Development of the Biosphere Task Force Meeting, International Institute for Applied Systems Analysis, Laxenburg, Austria, 27–31 August, 1984.

recognizing the geopolitical risk of today's dependence on OPEC oil and becoming increasingly aware of the environmental consequences of fossil fuel consumption. Natural gas offers unique opportunities for improvements on all the above counts. Efficiencies of gas in end-use conversions exceed those of oil and thus enhance energy conservation. Methane (CH_4) contains less carbon than oil, ie less carbon dioxide (CO_2) emissions and is essentially free of sulphur dioxide (SO_2). And methane is geographically a more evenly distributed resource even by traditional resource assessment standards. 'Almost a hundred countries have proven gas reserves adequate for commercial exploitation'.[9]

Furthermore, natural gas fits better into the increasing complexity of our industrialized infrastructure where flexibility through integration becomes more and more important. In other words, oil (technologies) appear to have reached, at least in the industrialized countries, a maximum degree of maturity within a technology's life cycle. This does not imply that the days of oil are numbered in the near future. As Figure 1 shows, substitution in the primary energy market is a slow process and it takes some 60 to 80 years for a new energy form to reach a market share of 50%. Therefore oil will continue to be the dominant fuel well into the 21st century.

The question arises how can one introduce technological change into natural gas studies without drifting off into science fiction but still grasp the essential technology prospects which will emerge in the near, medium and far future. The technology substitution dynamics of the past provide an upper limit for the market penetration of natural gas, ie the slopes of the curves in Figure 1 serve as a measure of how fast infrastructures and societies can adopt a new form of energy at a macro level. Actually, natural gas has been contributing to the global energy mix for quite some time – though before the 1970s primarily in North America – and thus is not an absolute new source of energy. What is important in the context of natural gas studies concerns the degree of maturity of the gas industries and their associated technologies.

So far natural gas has been the stepsister of oil. First of all natural gas production has been a byproduct of oil production. Also until recently most of the non-associated natural gas reserves have been discovered in the search for oil. One major implication of this inlaw relationship is that despite the obvious physical differences natural gas has been an 'oil technology' rather than a technology in its own right.

At the end-use side natural gas happened to fit the existing distribution and consumption infrastructure, a reminiscence of the old town gas era. Without major infrastructural adaptation it was possible to economically market an oil production byproduct.[10] However, energy policies in many countries have not reflected the value of natural gas for their respective economies. Either end-use prices were kept at extremely low levels at a fraction of directly competing fuels (essentially oil products and electricity) while at the same time strict controls inhibited the use in certain economic sectors; or prices were raised above competitive levels (gas premium) so as to reflect the perceived scarcity of oil and gas reserves. The latter attitude invited the appearance of the USSR and Algeria on the European gas market. This in turn opened the whole array of supply security issues. The result, in one way or another, was an artificial imbalance between natural gas demand and supply which still dominates the thinking of many strategic planners.

[9]Tempest, *op cit*, Ref 6.

[10]In addition, during the 1960s the western European natural gas market received its initial growth momentum from the cheap gas of the large Dutch Groningen field. Without the Groningen gas the European gas market might not have developed until the development of the North Sea after the first oil price hike in 1973/74 if at all.

Hence statistical evidence on methane technology productivity has been distorted by this close association with oil. An assessment of future natural gas prospects based on an implicit technology transfer from oil to methane therefore most likely misses the true potential for natural gas. In a first step, one must acknowledge and understand the geological and technological differences between oil and methane. With regard to geology natural gas is 'not limited in commercial quantity by the unique trapping circumstances necessary for the commercial production of oil' and thus geographically more evenly distributed than oil. The failure in oil exploration in the past made 'many countries believe that they possess little or no natural gas'.[11] Meanwhile quite a few countries have been successful in their gas exploration activities.

Technically the difference between oil and gas concerns the physical properties of methane, ie natural gas is compressible, liquid oil is not. This means that 'gas can be produced from rocks through which oil cannot even move. Additionally, a barrel of oil produced from 30 000 feet is still a barrel of oil at the surface; whereas a barrel of gas at 30 000 feet can be as many as 500 bbl of methane at the surface. Thus, as one drills deeper, the quantity of gas recoverable from any given reservoir is increased by each additional increment of pressure, and reservoirs of lesser quality become more and more capable of commercial gas production'.[12]

Unlike oil, natural gas reserves are not confined to a maximum depth because of pressure considerations. The greater depth of natural gas reserves, ie because of pressure, temperature and rock conditions, requires, for commercial methane production, different and more advanced drilling technologies than those deployed in oil production. Today, methane exploration, drilling and production technologies suitable for gas from deeper and tight formation fields are in their embryonic stages of development. Over time these technologies will mature and their productivity will increase so as to make the production of methane from fields other than conventional oil domains a commercially viable undertaking. One should note that these technologies are primarily addons to existing infrastructures and technologies and do not imply quantum jumps like technical breakthroughs. What is required is a quantum jump in perception. As much as the automobile industry became an industry in its own rights once the step from adding an engine to a horse cart towards an integrated automobile design was accomplished, methane technology will gain momentum once emancipated from oil technologies.

Similar evolutions will also be experienced at the levels of gas transmission, distribution and end-use conversion which will further enhance the efficiency of gas use compared to other fuels, contribute to the improvement of vital environment conditions and function as a chemical tether for industrial development and integration. And there are two major energy consuming sectors which traditionally have not been the focus of methane marketing strategies – electricity generation and the transport sector. The former market has been foreclosed because of institutional regulations in many countries while the latter suffered from an economic methane-to-synthetic gasoline conversion technology.

In the long run, both markets offer opportunities for methane accommodation. Environmental considerations and sociopolitical acceptance problems associated with nuclear power in particular and

[11]Robert A. Hefner III, 'Natural gas – the politically and environmentally benign least-cost energy for successful 21st century economies, the energy path to a better world', paper presented at the First International Conference on Shallow Oil and Gas Resources, The GHK Companies, Oklahoma City, USA, 1984.
[12]*Ibid.*

megaprojects in general may pave the way for gas into the electricity generating sector. New technologies, like highly efficient multi-stage combined cycle turbines in the kW to MW range, could be instrumental in a shift from centralized to decentralized electricity/cogeneration systems. These combined cycle units appear to have relatively flat economics-to-scale prospects which implies increased flexibility in unit sizes. At times of highly uncertain electricity demand outlooks this is of importance for utility capacity planning. Small unit sizes quasi available off-the-shelf and short construction periods of six months or so would significantly reduce upfront capital requirements and thus decrease the risk of utility investments.

Without an efficient methane-to-gasoline conversion process methane use in non-stationary applications will remain inferior to oil based motor fuels. Although many research activities are targetted towards the development of a direct (catalytic) conversion process, additional efforts are required before commercial availability can be achieved. Such a technical breakthrough would have a favourable impact on the prospects for natural gas in developing countries in terms of both domestic energy supplies and gas exports simply because the transport economics for a liquid (at ambient temperature and pressure) would correspond to those for conventional oil products.[13]

Most energy projections avoid the difficulties of dealing with the impact of increasing knowledge on resource availability or on energy prices. Indeed, projecting the dynamics of productivity performance or innovation is a highly uncertain and risky undertaking but a necessary step in order to understand longer term energy demand and supply. The omission of innovation and new technologies explains, at least partly, the poor track record of conventional energy studies. The following paragraphs compare the differences of these conservative and risk averse approaches with an attempt to introduce technical progress in a long-term gas study.

The impacts of technical change on the European gas market

Technology and policy

The European gas market is characterized by a highly uncertain gas demand outlook which, to a large extent, is a direct consequence of even more uncertain gas supply prospects. Medium to longer term gas supplies, though plentiful in terms of available reserves and resources, are either only of marginal economic attractiveness (given current energy price profiles and state-of-the-art technologies) or stem from politically diverse sources. The agreement on the development of the highly capital intensive Troll field between Statoil and a European Consortium led by Ruhrgas AG signed in spring 1986 could have stabilized the supply outlook had the timing not coincided with the fast decay of world oil prices. Since Ruhrgas has not been receptive to an open gas-to-gas competition (cheaper gas deliveries could have been made available by the USSR),[14] it occurs that the 'commercial realities'[15] are not necessarily those factors which determine the levels of domestic gas production and dominate the negotiations of gas import contracts. The influence of 'non-commercial realities', ie national macroeconomic objectives and gas resource policies, foreign trade relations, geopolitics and supply security concerns, overshadows the technically feasible and economically viable market potential for natural gas in western Europe.

[13]The economic failure of the New Zealand methane-to-gasoline conversion effort is a direct consequence of the indirect (two-stage) conversion process. Since both stages (gas-to-methanol and catalytic methanol-to-gasoline conversion) are associated with conversion losses (overall thermal efficiency of 54%), the economics did not turn out right despite relatively low natural gas prices.

[14]Actually, Ruhrgas used the bulk availability of USSR gas at attractive prices both as a negotiating card in the Troll contract talks and as an incentive for the Netherlands to extend their gas export contracts for at least another 10 years. The threat of Soviet gas changed the initial Norwegian expectation of a premium for the high-cost but secure supplies from within western Europe to market-related prices. Indeed, the Netherlands also extended their major export obligations for another 10 years.

[15]Jonathan P. Stern, *International Gas Trade in Europe: The Policies of Exporting and Importing Countries*, Heinemann Educational Books, London, UK, 1984.

Therefore, apart from technical improvements, the competitiveness of natural gas in various energy markets will depend on a variety of related economic and institutional factors. Most importantly, there are the problems of the large upfront investment volumes in the methane transport infrastructure, the terms of actual sales contracts, gas pricing principles, take-or-pay clauses, etc but also political acceptability of gas deliveries from certain regions or gas purchases motivated by considerations other than volumes and prices. Generally contracts including all these factors have to be signed prior to any investment in the gas production and transmission system (see Troll agreement). And once a contract has been signed, both producer and importer are locked into this arrangement for as long as 20 to 30 years. The need for such long-term contracts is the combined effect of the enormous upfront capital requirements and the long payback periods associated with significant natural gas projects. Though economically viable on a pure calculatory basis private investors are not willing to assume the economic risk involved or the absolute level of capital outlays exceeds the financial capability of individual utilities. Consequently, government involvement has become the rule both for guarantee purposes and resource management. Hence, gas markets have become more and more regulated at a time when there has been a converse tendency – the growing spot market for oil and coal.[16]

The net effect of these institutional constraints can be summarized into the currently dominating wisdom that European natural gas demand is more price elastic with respect to rising than to falling prices.[17,18,19] Clearly, the gas delivery contracts and their underlying pricing principles reflect either the objective of supplying gas at prices competitive *v* alternative fuels, the costs of avoiding the use of alternative fuels or, in some extreme cases, oil price parity at the point of production. Whatever case may be applicable, the determination of the sales price for gas ranged at the upper end with respect to burnertip competitiveness, given the existing technical environment. Any rise in prices, therefore, would cause a stronger response than a corresponding decline.

The IIASA gas study assessed the technoeconomic potential for natural gas in Europe assuming a gradual relaxation of most internal (ie national or regional) policies and institutional constraints effectively distorting gas' competitiveness in various energy markets. These relaxations include, for example, banning gas from certain applications (electricity generation) or protectionism of electricity *v* gas in end-use markets or active gas-to-gas competition. The latter aspect creates a more favourable position for continued oil (and coal) substitution. Current geopolitical and supply security considerations which affect import volumes from some of the politically diverse sources served as guidelines – in the short run – for the natural gas trade flows but not as hard-wired limits or import ceilings.

Since institutional limits are difficult to project, one of the prime objectives of the IIASA study concerned the impact of a changing technical environment on the future prospects for natural gas. Consequently, technical progress constituted one of the most crucial scenario parameters in this study. Indigenous resource extraction costs and market prices were based on marginal (levelized) costs plus royalties (profits) and government take. Also there existed no link between domestic oil/oil product prices and methane prices. Import prices for

[16]Government regulation will certainly continue to impact international gas trade but also will be visible in most national markets. The recent deregulation of the US gas market is a consequence of the adverse effects of the price controls by the Natural Gas Policy Act. In essence this act created a split gas market. Pipelines crossing state boundaries (interstate pipelines) as well as the wellhead pricing of such transported gas have been subject to federal regulation and jurisdiction. Hence, if a producer sold gas to an interstate pipeline system, the price was regulated. If sold within the state produced the price was determined by local competition primarily. The net effect was ample supply of relatively cheap local gas and a regulation-induced shortage of cheap interstate gas. In 1978 efforts to rectify this distorted situation led to a partial regulation of the intrastate market. In 1985 gas from certain vintages and deep or tight formations was decontrolled which was the turning point to further deregulation steps.

[17]Purvin and Gertz, *Western Europe Natural Gas Industry Market and Economic Analysis to 2000*, London, UK, 1982. Purvin and Gertz, *Western Europe Natural Gas Industry Market and Economic Analysis to 2000*, London, UK, 1984.

[18]H-H. Rogner, S. Messner, M. Strubegger and A. Golovine, *The IIASA International Gas Study*, Discussion paper for Gas Meeting at Krainer Hütte, International Institute for Applied Systems Analysis, Laxenburg, Austria, 17–18 October, 1985.

[19]Simon A. Blakey, 'Europe's natural gas industries', in Melvin A. Conant, ed, *The World Gas Trade: A Resource for the Future*, Westview Press, London, UK, 1986.

crude oil, oil products, and coal were exogenously determined, while gas import prices were the combined result of a weak link to oil prices and the concept of long-term marginal resource rents.

The Conventional Technology Scenario

The Conventional Technology Scenario represents a business-as-usual scenario where technical progress was assumed to follow trends that have emerged since the first oil price hike in 1973/74. In particular, the Conventional Technology Scenario includes energy productivity improvements on the energy end-use part of the energy system such as industrial boilers, furnaces, etc and residential/commercial space heating technologies and appliances. One should note that energy saving measures such as better energy management or the existing standards for the insulation of the housing stock have been accounted for in the useful energy demand scenario calculations. By the same token the industrial useful energy demand assumptions already reflect the effects of the anticipated economic structural change.

Since technical progress is not restricted to one particular fuel or technology, and not to discriminate between fuels, a uniform efficiency growth rate was applied to each category of end-use technologies. Roughly, an efficiency increase for thermal conversion purposes of some 25% in the residential and commercial sectors and of 15% in industries was applied.

Burnertip competition was the decision criteria in the calculations for the cost-optimal primary energy mix. Given the current glut in all European energy markets, a 'demand creates its own supply' situation was assumed for the short run. Competition between energy imports and indigenous production becomes a central issue where vintage structure and sunk capital cost considerations play a dominant role. Consequently, within the infrastructure framework of the energy system fuel switching or interfuel substitution is primarily a function of relative prices.

In the long run, energy supply appeared not to be resource constrained and a least-cost supply strategy based on essentially state-of-the-art technologies was pursued. Table 2 contains the international oil market price development underlying the IIASA analyses.

The results of the IIASA Conventional Technology Scenario are summarized in Figure 2. The Conventional Technology Scenario development of the West European primary energy mix in Figure 2 corresponds to the findings of most other energy studies such as *Energy 2000* of the Commission of European Communities (CEC),[20] Data Resources Inc,[21] the Economic Commission for Europe (ECE)[22] (see Table 3) or implicitly the International Energy Agency (IEA).[23] Unlike the IIASA, CEC and ECE projections, which account for the dynamics of the entire primary energy balance, the IEA study only reports future natural gas developments for western Europe. However, the evolution of the primary energy system underlying the IEA gas analyses by and

[20]Commission of European Communities (CEC), *Energy 2000*, by J-F. Guilmont, D. McGlue, P. Valette and C. Waeterloos, Cambridge University Press, 1986.
[21]Data Resources Inc, *The DRI Report on Natural Gas Markets in Europe*, Paris, 1984.
[22]Economic Commission for Europe (ECE), *Energy Data Bank*, Geneva, 1986.
[23]International Energy Agency (IEA), *Natural Gas Prospects*, OECD, Paris, 1986.

Table 2. Oil price development in the Conventional Technology Scenario, 1980–2030 (%).

	1980	1985	1990	1995	2000	2010	2020	2030
1985 US$/bbl	39.8	27.8	22.5	25	27	33	44	49
1985 ECU/bbl[a]	45.1	31.5	25.5	28	31	38	50	56

[a]ECU – European currency unit.

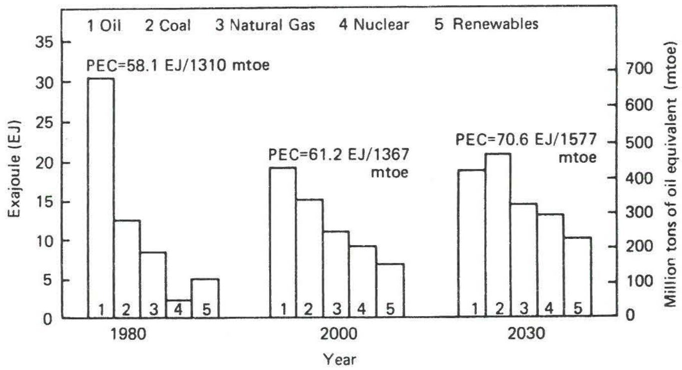

Figure 2. Western Europe, Conventional Technology Scenario, primary energy consumption, 1980–2030.

Table 3. Primary energy mix of major energy studies (%).

	1980[a] IIASA	ECE	CEC	2000 IIASA	ECE	CEC
Oil	52.7	53.0	53.6	35.0	35.1	38.6
Coal	21.3	21.2	23.0	23.5	23.4	23.2
Natural gas	14.3	14.7	17.5	17.3	16.9	17.3
Nuclear	3.8	3.9	4.4	13.6	19.3	18.9
Hydro and other	8.0	7.2	1.6	10.6	5.3	1.8
Total	100.0	100.0	100.0	100.0	100.0	100.0

[a]Difference in 1980 because of geographical dissimilarities and different conversion factors.

large resembles the CEC and ECE projections.[24] The commonalities of these projections include:

- substantial displacement of oil to less than 40% by the year 2000;
- significant increase in the contribution of nuclear power;
- a constant share for solid fuels (hard coal and lignite); and
- constant to, at best, slightly increasing shares for natural gas.

Dissimilarities between these studies relate primarily to the evolution of primary energy consumption in absolute terms, the rate of expansion of nuclear power and the future contributions of renewable energy sources. The IIASA primary energy growth rates fall behind those of the CEC, ECE and IEA which are the result of different expectations regarding future economic growth rates, the assumed rate of structural change and the improvements in energy performance. For example, the CEC study bases its energy consumption projections on a gross domestic product (GDP) expansion of some 2.8%/year for the period 1984–2000 (IIASA 2.3%). In contrast to a lower economic growth expectation, the IIASA study assumes a more progressive improvement in the energy intensity than the CEC. The combined effect of these assumptions translates into diverging primary energy growth rates or primary energy–GDP elasticities of 0.22 in the IIASA study and of 0.51 in *Energy 2000*, respectively.

In the IIASA study the contribution of nuclear power does not reach the market shares achieved in the ECE, IEA and CEC analyses. Two major reasons account for this difference. First, the lower economic activity underlying the IIASA projections. Second, the IIASA study was completed in Autumn 1986 and thus accounted for both recent changes in public attitudes towards nuclear energy and the generally lower energy price profiles than those prevailing one or two years ago.

Of interest is also the distribution of methane use between various

[24]When comparing the numerical findings of these studies one should bear in mind that there are some geographical dissimilarities regarding the regional aggregation used by these studies. The CEC study includes the EC-10 members, the IEA study compasses OECD-Europe, the ECE aggregation accounts for all west European countries, while the IIASA regional aggregation also includes Yugoslavia in western Europe. Therefore any discussion of, and comparisons between, these studies will be restricted to relative terms such as the evolution of the primary energy mix in terms of percentage shares, etc. Furthermore, the study horizon of the IIASA study extends to the year 2030, the IEA study horizon ends by the year 2010 while the CEC and ECE projections do not look beyond the turn of the century. Therefore the year 2000 will be used as a reference year for the comparison of future primary energy trends.

energy consuming sectors, the dynamics of which take different directions in these studies. While both the ECE and CEC projections foresee a significant decline of gas as a fuel for electricity generation by the year 2000 (see Table 4 which depicts a reduction of 5.6 and 7.1 percentage points respectively), the IIASA and IEA studies do not anticipate such a strong reduction in gas use for this sector (minus some 3.5 percentage points). ECE, IEA and CEC project a growing gas reliance of the residential/commercial sectors which offsets the decline in the electricity sector (and in the cases of the IEA and CEC also of the industrial sector) while in the IIASA analyses a shift from the residential/commercial to the industrial sector occurs.

Explanations for these diverging trends can be derived from:

- the low GDP–primary energy elasticity of the IIASA study which implies an even stronger restructuring of the industrial sector and a shift to more efficient and more flexible industrial boilers and furnaces than assumed, eg in the CEC study;
- the explicit inclusion of energy consumption density categories and category-specific natural gas distribution costs in the IIASA study may have discriminated gas use in low density areas;
- the general tendency of the IEA and CEC to favour coal over oil and gas in the industrial and central conversion sectors;
- in the IIASA study no energy carrier was barred from any specific energy sector; and
- the longer time horizon of the IIASA study until the year 2030 which automatically includes a different, ie larger and less geopolitically constrained, energy resource availability concept.

In summary, the IIASA Conventional Technology Scenario repeats, on the aggregate, the qualitative projections of the ECE, IEA and CEC. By and large this is not an unexpected result. The basic assumptions regarding energy resource availability, energy production and conversion technologies or energy transportation infrastructures follow similar trends. However, on a more disaggregated level, the agreements between these studies begin to disappear. The explicit introduction of technical progress for the energy conversion facilities of the industrial and residential/commercial sectors as well as the unrestricted, ie by energy policy, use of natural gas in all sectors resulted in diverging energy consumption profiles. The expansion of technical progress to the energy supply system, therefore, should result in a further divergence of such future trends and eventually be even felt at the aggregate level of primary energy consumption.

Table 4. Sectoral distribution of natural gas consumption, 1980–2010 (% and billion cubic metres).

	1980				1990				2000				2010			
Sector	**IIASA**	**IEA[a]**	**ECE[b]**	**CEC**	**IIASA**	**IEA[a]**	**ECE[b]**	**CEC**	**IIASA**	**IEA[a]**	**ECE[b]**	**CEC**	**IIASA**	**IEA[a]**	**ECE[b]**	**CEC**
Industries	33.7	38.2	34.5	35.6	36.5	33.6	34.1	32.3	39.3	36.4	35.1	34.6	40.9	39.0	–	–
Non-energy	1.3	–	2.6	4.2	2.0	–	2.4	4.9	3.2	–	2.4	5.7	4.6	–	–	–
Residential/ commercial	44.7	44.6	44.4	40.8	40.4	49.2	46.9	44.8	38.9	47.5	49.9	47.4	37.0	48.5	–	–
Transport	0.7	0.2	0.2	0.2	0.6	0.2	–	–	0.5	0.4	–	–	0.4	0.3	–	–
Central conversion	15.4	14.1	18.2	14.6	14.8	13.1	16.6	13.1	12.8	11.4	12.6	7.1	11.4	8.2	–	–
Losses	4.2	2.9	–	4.5	5.7	3.9	–	4.9	5.3	4.3	–	5.2	5.7	4.0	–	–
Total	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	–	–
Total in bcm	219	214	201	203	256	244	261	228	290	280	277	235	328	305	–	–

[a]IEA – High Demand/Low Oil Price Scenario; non-energy use included in industries.
[b]Losses included in central conversion.

The Technical Evolution Scenario

The Technical Evolution Scenario extends the technical progress beyond the end-use technologies to all stages of the energy chain from resource extraction to end-use conversion. Apart from improving existing or conventional technologies, this scenario also implies the availability and introduction of new exploration and production technologies, advanced equipment for the construction of gas mains, new maintenance and monitoring systems for pipelines, as well as direct methane-to-gasoline conversion, new electricity/cogeneration and other advances in energy end-use technologies. Table 5 contains a summary of advanced technologies which potentially may become instrumental for future productivity improvements along the entire gas chain.

The most crucial assumptions in this Technical Evolution Scenario concern the productivity growth rates in the drilling sector, the methane transport system and the availability of highly efficient methane-to-electricity conversion facilities. The assumed 4.5% annual productivity improvement for drilling in tight formations corresponds to an order of magnitude over the next 50 years which translates into a proven

Table 5. Current and future technical advances along the gas chain.

Stage of the gas chain	Technologies[a]	Productivity increases assumed in the Technical Evolution Scenario[b]	
Exploration	Satellite search, aeromagnetic mapping, carbon and helium isotope ratios, computerized geochemical and geophysical prospecting, vegetative anomalies, etc	Proven gas reserves	2.5%/year
Drilling/ production	Measurement while drilling, smart down hole electronics, polycrystallic diamond bits, improved drill pipe and casing materials, improved down hole motors, tunnel concepts, sea-bed platforms, gas treatment, etc	Onshore conventional Onshore tight formation Offshore deep water	2.0%/year 4.5%/year 2.5%/year
Transport – pipe	Large diameter pipes, higher pressures, automated pipe laying techniques, etc	Average improvement	1.0%/year
– LNG	Magnetocaloric refrigeration	Average improvement	0.75%/year
Distribution	Ground-piercing impacters, pipe pushers, compacting augers, new accurate horizontal drilling techniques, improved maintenance and monitoring systems, pavement cutting, greater mechanization and automatization, new materials, etc	Average improvement	1.25%/year
Electricity/ cogeneration	Combined cycle gas turbines, fuel cells	As of 1990	0.75%/year
Industries	Steam injected turbines for cogeneration, heat pumps, gas desiccant cooling systems, new industrial furnaces, forced drought immersion, oxygen/ natural gas burners, recuperative burners, control systems, modular concepts, etc	Average conversion efficiency	0.5%/year
Commercial	Condensing water heaters, heat pumps, cooling systems, heat recuperation, etc	Average conversion efficiency	0.75%/year
Residential	Heat pumps, new furnaces and water heaters, condensing and exhaust heat recovery, control systems, etc	Average conversion efficiency	0.75%/year
Transport	CNG, catalytic methan to gasoline conversion	Costs for methane based motor fuels	2.0%/year

[a]Incomplete list.
[b]The IIASA study used simplifications and aggregations of new technical developments. The productivity increases have to be viewed through the lens of gross averages.

methane reserve growth rate of some 2%/year (for oil corresponding considerations result in less than 0.5% annual reserve expansion).

Transmission and distribution costs for natural gas dominate even in such ultra high cost producing areas as Troll or Sleipner in the North Sea (see Table 6). Hence, high productivity increases yielded in the gas exploration and drilling sector will render insufficient unless similar evolutions can be materialized for methane transport and distribution systems. This will be particularly important because of growing distances between gas resource locations and consumption centres. Rough estimates suggest a tripling of methane travel distances between today and the turn of the century.[25] In the longer run one might expect a trade-off between high cost production close to the point of consumption versus inexpensive production and long distance transmission.

The productivity growth rate for the transmission and distribution of natural gas (potential improvements are listed in Table 5) in the Technical Evolution Scenario amount to some 1.2%/year. Other essential productivity increases have been projected for gas-fired combined cycle turbines. Gas turbines have been a technological spin-off from aircraft jet engines and thus continue to benefit the research and development efforts regarding better turbine materials and designs. The serial combination of combustion and steam turbines currently yields efficiencies of 47% to 48% (electricity only) and more than 80% of fuel utilization in cogeneration applications. Ongoing research to improve material degradation at high combustion temperatures as well as other accompanying activities suggest additional productivity gains for gas-fired combined cycles and an efficiency of more than 60% (electricity) appears technically feasible in the not so distant future (within a 50 year planning horizon).

The overall impact of the introduction of technical progress on the dynamics of natural gas in the west European energy market is portrayed in Figure 3. The corresponding market shares are given in Table 7.

[25]Michel Valais, 'World natural gas prospects', *Energy Exploration and Exploitation*, Vol 1, No 4, 1983, pp 269–276.
[26]M. Strubegger and S. Messner, *The Influence of Technological Changes on the Cost of Gas Supply*, Working Paper WP-86-38, International Institute for Applied Systems Analysis, Laxenburg, Austria, 1986.

Table 6. Cost structure for methane deliveries in central Europe (adapted from Strubegger and Messner).[26]

	Cost structure (%)		
	Extraction	Transport	Distribution[a]
Groningen	6	4	90
NL offshore[b]	9	6	85
Ekofisk	16	11	73
Statfjord	16	19	65
Sleipner	27	11	62
Heimdel	32	11	57
Troll	27	17	56
Gullfaks	34	15	51
Troms[c]	26	26	48
Troms[d]	25	28	47
Algeria	4	28	68
Algeria (LNG)	4	36	60
Nigeria	5	36	59
Nigeria (LNG)	4	43	53
Persian Gulf[e]	4	32	64
Persian Gulf[f]	3	35	62
Persian Gulf (LNG)	3	44	53
Urengoy	8	34	58
Other/western Siberia	10	35	55

[a]Distribution costs have been averaged and kept constant for all cases.
[b]NL – Netherlands.
[c]Onshore pipeline via Sweden to Hamburg.
[d]Offshore pipeline to Emden.
[e]Pipeline transport via Yugoslavia.
[f]Pipeline transport via Italy.

Table 7. Primary energy mix, Technical Evolution Scenario (TEC) and Conventional Technology Scenario (CONV) (%).

Source	1980	2000 TEC	2000 CONV	2030 TEC	2030 CONV
Oil	52.7	35.6	35.0	22.6	24.3
Coal	21.3	19.2	23.5	20.3	26.8
Natural gas	14.3	20.5	17.3	25.9	18.9
Nuclear	3.8	13.8	13.6	17.0	16.7
Hydro and others	8.0	11.0	10.6	14.2	13.2
Total	100.0	100.0	100.0	100.0	100.0

Compared to the Conventional Technology Scenario, Figure 3 reveals not only a substantially different evolution for the west European primary energy mix but also a 10% reduction in total primary energy consumption by the year 2030 (4% by 2000). First of all, technical progress bettered the overall energy system's efficiency. Second, there is a major shift in the composition of primary energy consumption, essentially from coal to natural gas, which further improved the energy system performance. Finally, natural gas has become the largest single primary fuel in western Europe by the year 2030 (market share: 26%).

The evolution towards a gas dominated European energy system begins to emerge already by the turn of the century though not repeating the growth dynamics historically observed with oil:

- The market share of natural gas exceeds the 20% mark.
- Coal loses almost 4% of its market share and declines to an historical low (since the industrial revolution) of less than 20%.
- The displacement of oil is only marginally affected by the Technical Evolution Scenario.

The gross consumption of natural gas expands from 220 billion cubic metres (bcm) in 1980 to 330 bcm by 2000 which is an increase of 43 bcm *v* the Conventional Technology Scenario. Because of the productivity gains underlying the Technical Evolution Scenario, these additional natural gas volumes do not translate into corresponding increases in gas imports. In fact, the overall gas import dependence from non-European sources is reduced by some 30 bcm to 95 bcm (by the year 2000). Similarly, oil imports decline by 6%, coal imports by more than 50%. Technical change not only lowered the absolute level of oil import requirements but also exerted pressure on the international oil market price. The oil price development shown in Figure 4 reflects the combined effects of the increased gas market share, the reduced

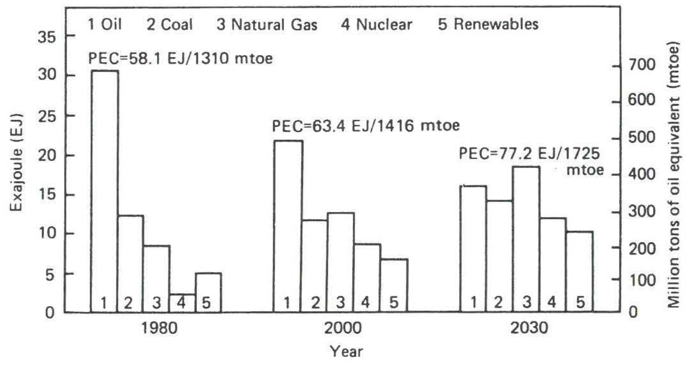

Figure 3. Western Europe, Technical Evolution Scenario, primary energy consumption, 1980–2030.

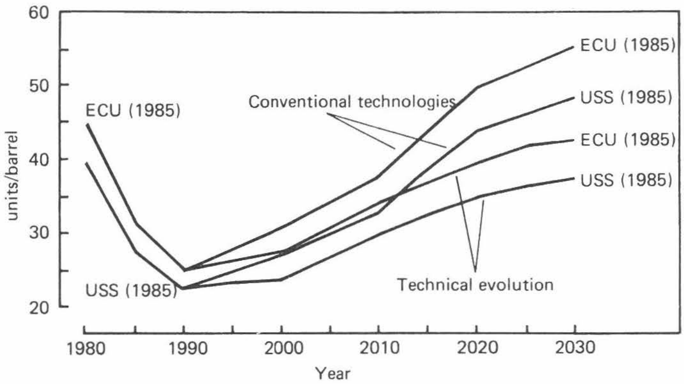

Figure 4. Oil price development in the Technical Evolution *v* the Conventional Technology Scenario, 1980–2030.

demand for oil imports and the positive impact of technical change on the cost profile of European oil production.[27]

After the year 2000 the market penetration of natural gas continues at the expense of coal and, to a lesser extent, of oil. In 2030 aggregate gas consumption amounts to some 480 bcm, 124 of which would originate from non-European sources. This implies an indigenous west European gas production of some 360 bcm or a doubling of current production levels.[28] The production level of 360 bcm is the result of the combined assumptions regarding technical progress for methane exploration (ie the resource base) and drilling (ie tapping the resource base). These by and large non-conventional views on the prospects of technological evolution directly translate into economics favouring gas over other fuels. In other words, the methane production projections of the Technical Evolution Scenario require the existence and the technoeconomic feasibility of tapping gas resources such as Devonian shales, tight sands, pure pressure aquifers, gas hydrates, subducted deep deposits and other abiogenic sources. For example, Hanneman[29] reports unconventional gas resources of just the USA at over 250 trillion cubic metres (tcm). This figure must be viewed versus the current official gas reserve figure of some 5.4 tcm. Again, one should note, there is no implication that these vast resources could be recovered with today's technology.[30]

The sectoral uses of natural gas in both scenarios are depicted by Table 8.[31] A comparison between the Conventional Technology and Technical Evolution Scenarios points to two reciprocal consequences of technical progress. These are the efficiency improvements introduced

[27]The price of natural gas imports from non-European sources varied between 70% and 80% of the international oil market price (fob at the European entry point).
[28]In the Conventional Technology Scenario gas imports amount to 135 billion cubic metres and indigenous production to 153 billion cubic metres.
[29]R.E. Hanneman, 'Methane technology: a technical survey', in eds, T.H. Lee, H. Linden, D.A. Dreyfus and T. Vasko, *The Methane Age*, Reidel, Dordrecht, Netherlands, in press.
[30]H-H. Rogner, S. Messner, M. Strubegger and E. Schmidt, *The Methane Age*, Working Paper WP-86-68, International Institute for Applied Systems Analysis, Laxenburg, Austria, 1986.
[31]The total natural gas consumption reported in Table 8 does not include losses in the transmission and distribution system (approximately 5%).

Table 8. Sectoral distribution of natural gas consumption.

	1980		2000 TEC[a]		CONV[b]		2030 TEC[a]		CONV[b]	
Sector	**(%)**	**(bcm)[c]**	**(%)**	**(bcm)**	**(%)**	**(bcm)**	**(%)**	**(bcm)**	**(%)**	**(bcm)**
Industries	35.2	72.6	34.0	106.3	40.2	108.5	28.5	124.0	43.7	160.4
Feedstocks	1.4	2.9	3.0	9.3	3.4	9.2	8.7	37.9	9.0	33.0
Residential/ commercial	45.4	93.6	30.4	95.1	39.9	107.7	23.7	103.2	37.0	135.7
Transport	0.7	1.4	1.0	3.2	0.5	1.3	6.6	28.5	0.4	1.5
Central conversion	17.3	35.7	31.6	98.8	16.0	43.2	32.5	141.2	10.0	36.6
Total	100.0	206.2	100.0	312.8	100.0	269.8	100.0	434.9	100.0	367.1

[a]TEC – Technical Evolution Scenario.
[b]CONV – Conventional Technology Scenario.
[c]bcm – billion cubic metres.

by new advanced technologies and the absolute level of fuel consumption. It appears that the efficiency improvements outbalance the additions in actual market shares. For example, in absolute terms the consumption of natural gas in the residential/commercial sector declines by some 12% from 108 bcm to 95 bcm while the share of natural gas within this sector remains fairly constant. Hence, the displacement of one fuel unit of conventional technology by a more advanced technology results in lower fuel sales; a fact many gas utilities observed in the past when their sales forecasts based on a one-to-one oil substitution strategy did not result in corresponding actual gas purchases.

The industrial sector is less sensitive than the residential/commercial sector and absolute methane consumption declines only marginally. New technologies allow for additional gas consumption in the low temperature heat market while electricity replaces gas in certain areas of high temperature heat applications. The latter is a comprehensive process phenomena rather than an energy particularity.

Considerable growth in natural gas consumption occurs in the central electricity and heat (cogeneration) sector and the transport sector. Both sectors experience more than a twofold increase in their gas consumption although the actual gas volumes are quite different. But these developments indicate a distinct structural change in the sectoral pattern of natural gas consumption. Natural gas as a final energy form, ie as a fuel at the energy end-use level, is losing in favour of gas in embodied form.

Already in the year 2000, and certainly more so by the end of the study horizon, any expansion of the gas market share at the level of primary energy translates into a fast penetration of natural gas into the electricity and eventually the transport sector. This also means that the industrial and residential/commercial markets offer little room for additional gas penetration. In both markets (burnertip) competition from district heat and electricity limit the use of methane. Instead, natural gas finds a growing niche as a valuable fuel for electricity and heat generation.

The percentage distribution of gas use of Table 8 confirms this trend. In the short run, the relative expansion of gas use for electricity generation occurs at the expense of the industrial and residential/commercial shares. Both sectors continue to lose market shares throughout the study horizon. But now the transport sector, instead of the electricity sector, gains the bulk share. Here, the assumption of a technically feasible and commercially viable methane-to-synthetic gasoline conversion process is a necessary prerequisite.

Conclusions

The Technical Evolution Scenario has shown that accounting for technical progress in long-term energy scenarios has a considerable impact on the future prospects for the west European energy system. In other words, major opportunities for an expanded use of natural gas, to a large extent, hinge on the successful development of new gas utilization and supply technologies. Although technology forecasting is as risky a business as any other forecast, there are definite benefits from the inclusion of technical change into medium- to long-term energy analyses. The principal benefit of such an exercise is to challenge conventional wisdom which tends to extrapolate the status quo of technical and economic conditions into the future. In the Technical Evolution Scenario extrapolation is of the essence also. However, here an attempt was made to extrapolate the dynamics of technologies and study their consequences for the future market penetration of natural gas. Another important factor concerns the mutual influence of energy policy and conventional wisdom. For example, the myth of the 1970s had it that natural gas is a scarce resource and kept in the ground would be worth more than in the market place. This perception changed with the discovery of major gas fields of the North Sea, particular of Troll, and the penetration of Soviet and Algerian gas into the European gas market. By the same token the environmental benignity of natural gas consumption has been used to request, at least, parity prices on equivalent calorific terms with oil. Technology, therefore, could be the vehicle to overcome these myths, turn submarginal resources into economically recoverable reserves and thus pave the way for natural gas to become a globally dominating fuel.

Given the current energy bubble, the spark for technical change to pick up momentum has to occur at the level of gas utilizing technologies. This is to say that, in the short run, improvements of existing boilers, furnaces, gas turbines as well as the simultaneous development of new gas consuming devices, cogeneration facilities or gas based industrial processes will be the stimulus not only for increased gas consumption but eventually also for the technology improvements on the gas supply-side.

The findings of the IIASA gas study report a market share of 26% by the year 2030. Compared with the technology substitution model, depicted in Figure 1, this is less than 50% of the market share derived from historically observed substitution dynamics. As a matter of fact, in the past the market penetration of methane has been slower than, eg, the displacement of coal by oil. Again, this observation points to the historical situation of gas as a dependent fuel, initially as a manufactured fuel from coal and later of oil. Current gas technologies are either old or oil-based technologies.

To that extent, the technical progress underlying the Technical Evolution Scenario may be too conservative, in particular, for those markets where the expansion of methane use encounters technical difficulties – the transport sector and feedstocks. Both sectors must eventually accommodate methane if the market share of natural gas is to exceed the 30% threshold.

The Technical Evolution Scenario is based primarily on technoeconomic considerations and omits all the equally important policy aspects, institutional, supply security and geopolitical factors. Combined, these factors may, or may not, impede the prospects for natural gas in the short- to medium term. It is then the task of technology to eventually mitigate these impediments. On the other hand, gas offers a viable alternative to the imminent environmental problems. On all counts, methane is superior to other fossil fuels.

The purpose of this exercise concerns the possible impact of future technical evolution on future energy mixes. The analyses attempt to show that the least likely event – no technical progress, which is the usual concept in long-term energy analyses – precludes intriguing alternatives *a priori*. This is not to say that the potential developments outlined here will become imminent. However, the crucial question is 'how well are we protected against future technical surprise while planning continues in a constant technology environment?' First of all this question is of importance for energy policy and research and development at the level of national governments and international organizations. And equally important for industries involved in long-term energy projects such as utilities, exploration, drilling and mining companies and energy equipment manufacturers.