PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A
MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

Natural Gas

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Natural gas

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This paper reviews the world's existing natural gas reserves and future expectations, together with natural gas consumption in 1972, by main geographic regions. The present and future supply and demand situation in each of the main natural gas markets, namely the U.S.A., the U.S.S.R., Japan and Western Europe, are discussed in the context of rising energy demand. The reasons are examined for the apparent paradox that, although now and for many years to come, the world has a theoretical abundance of natural gas reserves, in practice a number of important markets are already short or will soon be so. The paper will conclude by discussing the problems of meeting the developing future demand for natural gas with available indigenous production combined with supplementary supplies, including imports and manufactured substitutes.

1. INTRODUCTION

Compared with oil and coal, it is only recently that natural gas has become a commodity in international energy trade. Some important dates are:

1951 First major Canadian gas export by pipeline to the United States.
1964 First export of Groningen gas from Holland.
1964 First delivery of Algerian liquefied natural gas (l.n.g.) to the United Kingdom.
1968 First delivery of Soviet gas to Austria.
1969 First l.n.g. from Alaska delivered to Japan.
1970 First Iranian pipeline gas deliveries to the U.S.S.R.
1973 First Soviet gas deliveries to West Germany.

The reason for this comparative tardiness is quite simply that gas is more difficult to handle than oil or coal, and that the necessary technologies (larger diameter pipelines and l.n.g.), which are today taken for granted, have taken time to develop. One important consequence of this is that, although existing world gas reserves are plentiful, with good prospects of further discoveries, the major world gas markets (which are relatively few in number) are already, or are becoming, supply limited.

Looking ahead into the 1980s, although the flow of international trade in natural gas will most certainly intensify and multiply, it is unlikely, because of the delays which are inherent in the technological and political complexity of the many separate large projects which will be necessary, that such growth will be sufficient within this period to make any really effective change in the broad relation between world reserves and consumption which exists today.

A conclusion which can be drawn, therefore, is that there is a challenge which confronts the natural gas industry world-wide, together with the governments of the countries involved. It is to bring these abundant gas reserves economically, competitively and without undue delay to market, to the mutual benefit of both producer and consumer.

2. Existing world gas reserves

There are no generally accepted definitions of natural gas reserves and wide variations in both terms and estimating procedures may be met. For this reason what one country may classify as proven reserves cannot readily be compared with the proven reserves of another country, unless and until the definitions, quantification methods, energy values, composition, etc., are stated with some precision.

Further complications arise in quantifying exploitable reserves where gas is found dissolved in crude oil (solution gas) or in contact with underlying crude (gas-cap gas). Both are called associated natural gas and the volume of associated gas that can be recovered will depend mainly on the rate and the extent of oil production.

Because of these and other complications any world tabulation of gas reserves by country will almost certainly contain a wide variety of inconsistent data. However, these inconsistencies do tend to balance each other out to some extent and, in any case, are of less importance in the world picture than the relative broad regional disposition of world gas reserves.

With the foregoing reservations in mind, figure 1 indicates that known world gas reserves amount to some 53×10^{12} m^3, of which about one-third is located in the U.S.S.R., with one-sixth each in the Middle East and North America.

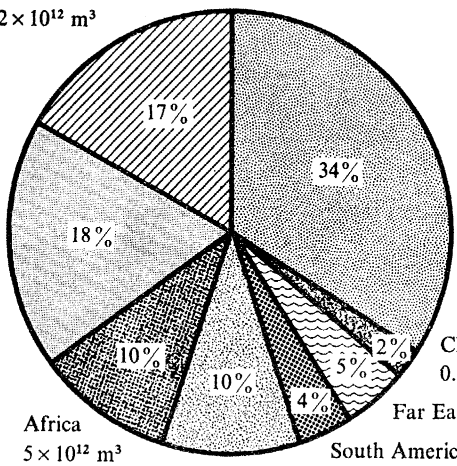

Figure 1. World gas reserves in 1972 – 53×10^{12} m^3 (equivalent to about 330×10^9 barrels of oil or 2×10^{21} J) (source of data: *Oil and gas journal*, December 1972).

On a thermal basis world gas reserves are equivalent to somewhere between one-half and one-third of world reserves of conventional crude oil (i.e. excluding tar sands and shale oil). Oil currently supplies about 45 % of world energy demand and is also the main source of primary energy in virtually every country. Natural gas supplies some 17 % of world energy demand (at first sight, a reasonable proportion in view of the relation between oil and gas reserves), but unlike oil its use, as will be shown, is concentrated in a relatively few countries. This limited geographic spread of gas consumption is because many gas reserves are distant from markets and because gas is more difficult and more costly to transport than oil. The absolute volume of world gas reserves is in fact overshadowed in present-day effect and importance by the relative proximity of such reserves to the main consuming markets. Thus, gas reserves in North America and Europe have been easier to develop and bring to market and hence have had a greater effect so far upon the pattern of world energy supplies than reserves in the Middle East.

In the future, as international trading in gas evolves from its present beginning, distant gas reserves will become economically linked to the world's major markets and a relation between world reserves and world demand will become more meaningful.

3. Expectations for future discoveries

With the notable exceptions of North America, the U.S.S.R. and Europe, natural gas has until recent years been much less attractive as an exploration objective than oil. With the emergence of international trading in gas and the increasing awareness of the need to maximize all energy forms, the position has changed and new gas discoveries may be economically attractive in many other areas.

Estimates of the future rate of discovery of gas reserves are fraught with precisely the same uncertainties as the assessment of future discoveries of oil or, indeed, any other minerals. Some geologists have predicted that ultimate recoverable gas reserves are likely to be of similar magnitude (on a thermal basis) to ultimate recoverable oil reserves, while others have been less optimistic. The indications given in figure 2 of the possible level of gas reserves that remain to be discovered should be regarded as being no less or more accurate than any other responsible prediction.

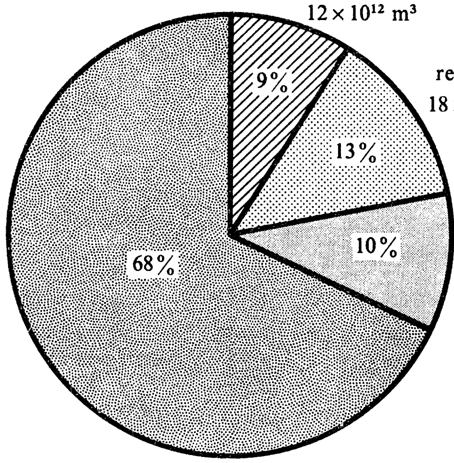

Figure 2. Expectations from new discoveries in addition to proven reserves – 140×10^{12} m^3 (equivalent to about 860×10^{9} barrels of oil or 5.25×10^{21} J).

Quite apart from the actual quantities of gas that remain to be discovered, which can be determined only after an exhaustive search over many years, there is the further imponderable of the extent to which economic incentives will exist to search for and develop all gas-bearing regions, particularly those situated in difficult locations or remote from the main consuming markets. Some sizeable gas deposits may be discovered but never in fact be developed because of economic considerations, technical complexity or because over time the potential market

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outlets for the gas may disappear as demand turns to other newer energy forms such as nuclear, hydrogen, etc. Forecasts of future gas discoveries should in addition be hedged with the same reservations as those already discussed in regard to existing reserves, that is to say that the contribution which new gas discoveries are likely to make to future energy demand will remain critically dependent on their location, the rate of development of the technology of gas transportation and (perhaps most important of all) the extent to which political, economic and commercial factors can be brought harmoniously together so that the necessary investments are made and facilities constructed.

So far this discussion has stressed the complexity of relating world reserves, both existing and future expectations, to demand. It is perhaps appropriate now to attempt to clarify the picture by examining where the demand for gas exists today and how it might be expected to develop in the years ahead.

4. World gas consumption

Historical data of world gas consumption are better documented and more precise than reserve data. Although the statistics for 1972 are still as yet incomplete, figure 3 is nevertheless thought to be a fairly accurate portrayal of world gas consumption by main region for that year. It shows that North America, essentially the U.S.A., is the world's largest gas market and that the U.S.A., the U.S.S.R. and Europe together account for nearly 90% of the world's total gas consumption. Excluding China and Eastern Europe, the balance of 6% for the 'rest of world'

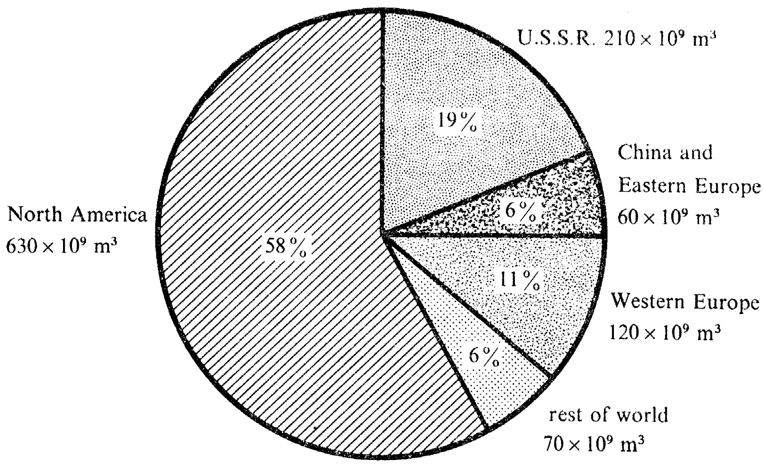

Figure 3. Estimated natural-gas consumption in 1972 – 1090×10^9 m³ (equivalent to about 7×10^9 barrels of oil or 43×10^{18} J).

represents a large number of small markets, e.g. Argentina, Australia, Bangladesh, New Zealand, Nigeria, Pakistan, Trinidad, Venezuela, etc., where natural gas is important in the local context but not in world-wide terms. Somethat different considerations, however, apply to Japan, one of the world's largest energy consumers. This is a relatively new market for gas which will become of increasing importance in the years ahead; the prospects for gas in Japan are discussed separately later in this paper.

Comparison of figures 1 and 3 shows some substantial regional variations between indigenous reserves on the one hand and consumption on the other. For example, whereas the U.S.A. is by far the largest gas market in the world, its share of more or less proven world reserves is at best only about 17 %, ranking third after the U.S.S.R. and the Middle East.

For the world as a whole the reserves: consumption ratio for natural gas (derived from figures 1 and 3) is just under 50:1, from which it might reasonably be concluded that there is an ample reserve base to satisfy expected market demands for many years ahead. However, as already mentioned, the practical, physical, political and commercial problems of developing and bringing to market a substantial proportion of these gas reserves are such that, for gas, global reserves: consumption or production ratios are not suitable yardsticks for measuring the true extent of the exploitable resource base in relation to present market demands. It is all a matter of timing; in due course a large part of these reserves will almost certainly flow to the world's markets, but today the necessary transportation systems are still being developed or (perhaps in certain cases) have yet to be invented. It would seem unlikely, however, that within the period under discussion (the 1980s) the development of such systems will be sufficient to change very substantially the broad picture as it exists today of ample world reserves coexistent with supply-limited markets. We thus have the apparent paradox that at this time, and for many years to come, the world has an arithmetic abundance of natural gas resources, while in practice a number of important markets are already experiencing or will soon experience supply shortages. Let us now look at the reasons for this in greater detail by examining the situation separately for each of the main markets of interest.

5. The U.S.A.

It is worth while considering in some detail the American natural gas scene, as many of the lessons which are being learnt in this market can in due course be applied elsewhere in the world where similar problems of demand outstripping supply are beginning to emerge.

For many decades the United States has enjoyed abundant supplies of indigenous energy, that is to say of coal, oil and natural gas. These resources have contributed significantly to the country's economic growth, national security and quality of life. In more recent years, however, development of new indigenous reserves of fuel have not kept pace with the growth in demand. A continued and increasingly severe deterioration of the energy supply position is predicted in the immediate years ahead by virtually all authoritative bodies both governmental and private.

In the case of natural gas, since 1966 annual production from the lower 48 states has been greater than new additions to reserves, with the consequence that the reserves: annual production ratio has declined from about 17:1 in 1966 to less than 11:1 in 1972. In other words, demand has been increasing appreciably faster than new additions to reserves. This statement still holds good even with the addition of Alaskan reserves, though these reserves are not yet in fact available to the market. The energy supply situation is exacerbated by the fact that oil demand, like gas, is also outstripping indigenous supply. For example, the U.S. Department of the Interior predicts overall U.S. demand for oil during 1973 at 2.8×10^6 m^3 (17.5×10^6 barrels)/day of which over a third, or more than 0.95×10^6 m^3 (6×10^6 barrels)/day will have to be imported. In the years ahead not only will demand rise but so will the percentage and hence absolute quantities of imported oil required.

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What then has led to this situation? Figure 4 shows the historical development of the U.S. primary energy consumption from 1950 to today, together with a forecast for the next few years ahead.

The average annual growth rate in consumption of gas between 1950 and 1972 was 6.2 %, compared with 5.3 % for oil; coal use actually declined between 1950 and 1960 and has since staged a recovery to much the same level it enjoyed in 1950. This high rate of growth of gas is a reflection on the one hand of its inherent clean and versatile qualities as a fuel, and on the other of the low selling prices imposed by the Federal Power Commission (F.P.C.), which is the governmental regulatory body for all inter-state natural gas activities. The average price of gas at wellhead for inter-state movements is still only about U.S.¢19/10^9 J (¢20/10^6 Btu). Within this average the wellhead price for new gas dedicated to the inter-state market was still as low as ¢25/10^9 J (¢26/10^6 Btu) in 1972, and only very recently and under certain special circumstances have prices for gas moving in inter-state commerce been free to rise to a level equivalent to those of other fuels. Gas sold at ¢25/10^9 J at the wellhead and delivered to New York is sold there at less than one-half the cost of oil. It is no wonder then that gas, quite apart from its many desirable physical qualities, has been and still is the preferred fuel.

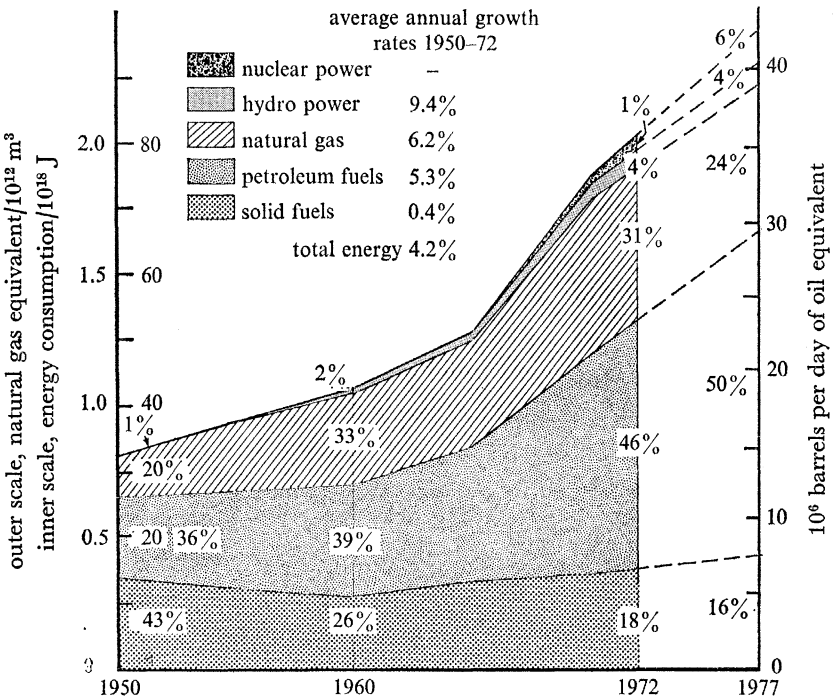

FIGURE 4. U.S.A., inland energy consumption and forecast, 1950–77 (excluding ships' bunkers and international aviation).

The consequence of this regulated low pricing policy has been that large quantities of gas have flowed into the intra-state market which is not subject to the same degree of stringent regulation, and into non-premium uses of gas such as for under-boiler fuel. More importantly, the policy has offered little incentive for the industry to explore for and develop new gas reserves for the predominant inter-state market.

A number of reports have been published by American study groups which conclude that

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a great deal more gas remains to be discovered in and around the United States. It is generally agreed, however, that much of this new gas is likely to be located on land at depths greater than 4500 m, in offshore structures, or in Alaska, and thus will be expensive (in the context of today's U.S. price structure) to find. Considerable exploration work is necessary before the extent of these new reserves can be determined with any degree of accuracy, but a reasonable assumption is that such new discoveries (excluding Canada) could reach as much as 9×10^{12} m^3 or very roughly the equivalent of the total presently proven reserves of 9.2×10^{12} m^3 in North America, i.e. including Canada. What is quite certain is that it will be costly and time-consuming to explore for and prove such reserves. Even if the appropriate financial incentives are forthcoming and new areas are made available for exploration fairly quickly, such new gas can even when found have little impact on overall supply availability for a number of years to come.

These supply constraints are beginning to be recognized by the U.S. Government, and President Nixon's Energy Message to Congress of April 1973 included proposals that indigenous gas from new wells, gas newly dedicated to the American inter-state market, and the continuing production of natural gas when contracts have expired should no longer be subject to price regulation at the wellhead. He also proposed the tripling of federal lease sales to stimulate new exploration effort. Moreover, in his State of the Union message in September 1973, the President urged Congress to take 'decisive action this year' on these matters. He proposed that 'we begin a gradual move to free market prices for natural gas by allowing the price of new supplies of domestic natural gas to be determined by the competitive forces of the market-place'.

How quickly and even to what extent these proposals may be approved by Congress remains to be seen, but in the present political climate it may be optimistic to expect an early resolution of these matters. Meantime because of supply difficulties an increasing number of gas distributors are having to curtail their sales in a variety of ways, such as by non-renewal of low-price contracts, refusal to accept new customers, etc. These actions, of course, impose a further burden upon the demand for other fuels and in particular for oil.

Apart from the discovery of new reserves, what are the other options open to the American gas industry? Basically these fall under two categories – imports of l.n.g. and the manufacture of synthetic natural gas (s.n.g.) from oil and coal. However, even under the most optimistic assumptions these supplementary sources of supply can in no way provide a sufficient supply base for gas to maintain the one-third share of total energy demand that it enjoyed in the late 1960s.

Taking s.n.g. from coal first, the problem here is not the availability of the resource base – the U.S.A. has vast deposits of coal much of which can be easily mined – but the technological complexity of converting coal to a high-energy gas compatible with natural gas. A substantial effort is being brought to bear upon this problem and a number of processes have reached the pilot-plant stage in the U.S.A. and a small-scale plant was recently commissioned in the U.K., but in spite of these encouraging developments it seems unlikely that large-scale commercial-size plants (say plants each capable of producing upwards of 2×10^9 m^3/year of s.n.g.) can be developed and brought into operation much before the late 1970s/1980. One reasonably realistic assessment of the contribution which s.n.g. from coal could make to gas availability in the U.S.A. is that 20–25 plants costing together some \$$5 \times 10^9$ to \$$6 \times 10^9$ could be on-stream by the mid-1980s, producing a total of around 60×10^9 m^3/year of s.n.g. (say 6×10^9 ft^3/day). The estimated cost of s.n.g. produced from coal must inevitably still be very tentative at this early stage of technological development. Current estimates based on coal prices of about \$8/tonne indicate ex-plant prices for s.n.g. at a high (92 %) load factor of at least U.S. ¢133/10^9 J (¢140/10^6 Btu) but commercial reality, when processes have been fully tested and built, may result in appreciably higher prices. To these prices will of course have to be added the cost of transporting the gas to market. Another factor to be taken into account in trying to predict the size of this source of supply is that since much of the coal required will have to be produced by open-cast mining, there may well be serious resistance on ecological grounds to massive developments on the scale mentioned above. For example, the production of 60×10^9 m^3/year of s.n.g. from coal could require as much as 170×10^6 tonnes of coal per year. If this were all or predominantly open-cast coal, and assuming 2.5 m thick coal seams, 70 km^2 of land would be need to excavated (and presumably rehabilitated) each year. The contribution that s.n.g. from coal can make to the U.S. energy demand may well therefore be constrained by technological and ecological problems, and perhaps also by price, in spite of the abundance of the raw material potentially available and in spite of the environmental advantage of producing a clean-burning fuel from coal containing varying proportions of sulphur. It is, nevertheless, likely to be an important contribution, the more so because it depends upon a secure source of supply.

Unlike s.n.g. from coal, commercial processes already exist for the manufacture of s.n.g. from oil fractions and such plants can now be built with confidence and brought on-stream in about two years from the beginning of construction. The constraint here is not of technological difficulty but rather that the feedstocks, naphtha-type fractions and gas liquids in particular are becoming increasingly expensive in line with all other oil products. This situation is aggravated by the fact that the ideal oil fractions for gas making are precisely the same fractions that are required as feedstock for the expanding petrochemical industry. Since the capital investment per joule of gas produced is lower for oil-based s.n.g. plants than it is for l.n.g. imports and for coal gasification, naphtha gasification may temporarily be employed to fill short-term needs, but as naphtha prices increase so the balance swings in favour of s.n.g. from coal and l.n.g. A substantial proportion of the naphtha required in the U.S.A. for gasification would have to be imported. Over 35 oil gasification proposals have been announced so far, of which one has been completed and a further seven are under construction. Whether the remaining proposals will materialize, and indeed many others yet to be announced, will depend upon the promoters' ability to secure a long-term supply of feedstock and, in appropriate cases, the necessary approvals from the F.P.C. As an illustration of the quantities that could be involved, over 95000 m^3/day (600000 barrels/day) of naphtha-type fractions would be required to produce some 25×10^9 m^3/year of s.n.g. (say, 2.5×10^9 ft^3/day).

Because the cost of making s.n.g. from oil is very sensitive to the price paid for the feedstock, the ex-plant cost of s.n.g. from oil can vary considerably, depending upon what assumptions are taken regarding future oil prices. Based on present price trends for oil, ex-plant gas prices could well rise to (U.S. ¢166/10^9 J (¢175/10^6 Btu) or more by the late 1970s.

It has been shown that the contribution that newly found natural gas and s.n.g. (from oil and from coal) can make to the American demand for gas in the years ahead may be limited by the long lead times required for exploration and subsequent development if the exploration is successful, by ecological problems, by inadequate and/or unproven technology, and by the cost of and limited availability of suitable feedstocks. Equally, imported l.n.g. is not the saviour. It too is constrained in its potential contribution to total gas supply.

Although a number of l.n.g. proposals have been announced, and are at varying stages of planning, only one major base load l.n.g. import scheme has (at the time of writing this paper) received all the necessary governmental consents and started construction. This is the first of El Paso's schemes from Algeria involving the import of some 10×10^9 m^3/year and starting in 1976. Other proposals have yet to receive F.P.C. approval and are still in the negotiating/planning stage. Nevertheless, in spite of this apparently slow start, it is probable that the U.S. will in due course be importing l.n.g. not only from Algeria but also from Nigeria, the U.S.S.R., the Middle East and perhaps Venezuela, Indonesia, South East Asia and elsewhere. The starting times for such projects are likely to fall between the late 1970s and the late 1980s. Depending upon what assumptions are taken regarding the attitude and steps the U.S. government will take to combat the developing energy shortage, the degree of cooperation that will exist in the future between the governments concerned, the economic viability of the projects for the commercial interests involved, and the availability of the necessary hardware (both plants and ships) and finance, it is possible to postulate a spread of likely l.n.g. import programmes for the U.S. ranging between 50×10^9 and 120×10^9 m^3/year by the late 1980s. Certainly the resource base in terms of gas reserves surplus to local needs exists in most of the supplying countries mentioned to support an even higher level of U.S. imports; however, experience so far indicates that the time required to put together complex international projects of this magnitude is such that these higher levels seem unlikely. Quite apart from the time needed for the design and construction of the necessary facilities, commercial and financial negotiations are time-consuming and the obtaining of the necessary governmental consents (at both ends of the supply chain) is inevitably a major limitation. As for prices, depending on the distance from the supply source to the import point and the volumes involved, the delivered price of l.n.g. imports into the U.S. can vary over a wide range. But even for the long-distance supply sources l.n.g. landed cost is still likely to be competitive with that of producing s.n.g. from oil and coal, and indeed with pipeline gas from Alaska. The techniques of liquefying natural gas and of ocean transport of l.n.g. are now proven on a commercial scale, and based on recent operational experience and allowing for capital and operating cost inflation in the years ahead a likely range of prices for l.n.g. delivered at U.S. seaboard in 1980 is between U.S. ¢95 and 142/10^9 J (¢100 and ¢150/10^6 Btu).

Perhaps the two main points to make in regard to the U.S. gas market are, first, that it has the capacity in the future to absorb the maximum levels one can reasonably envisage of all forms of supplementary gas including not only l.n.g. and s.n.g. but also any new indigenous gas that may be discovered on land or offshore, and yet still have an overall shortage in relation to the potential demand. This point is illustrated in figure 5, where a forecast is made for U.S. gas supply ahead to 1990.

Secondly, because supplies will be insufficient and new gas will be expensive, the marketing pattern must and will change. Low-priced large-volume steam-raising-type applications will be phased out and supplies will tend to be directed at those market sectors which can afford to pay higher prices and where the inherent qualities of natural gas can be used to the maximum advantage. This in return will create load-balancing problems for the pipeline systems of the gas distributors and impose a greater burden on other energy forms to fill the gaps that gas has historically supplied.

While it may be considered that these observations tend to paint a pessimistic outlook for gas in the U.S. market, it should be noted that even with these supply constraints the U.S. will remain for many years to come the world's largest gas market. Equally, it should be kept in mind that these problems offer a major challenge to meet which the entrepreneurial skills and capacity for technological effort and innovation of the industry are certainly being mobilized with support from the government; a struggle is under way, the outcome of which may differ, markedly from that predicted here on the basis of facts available today.

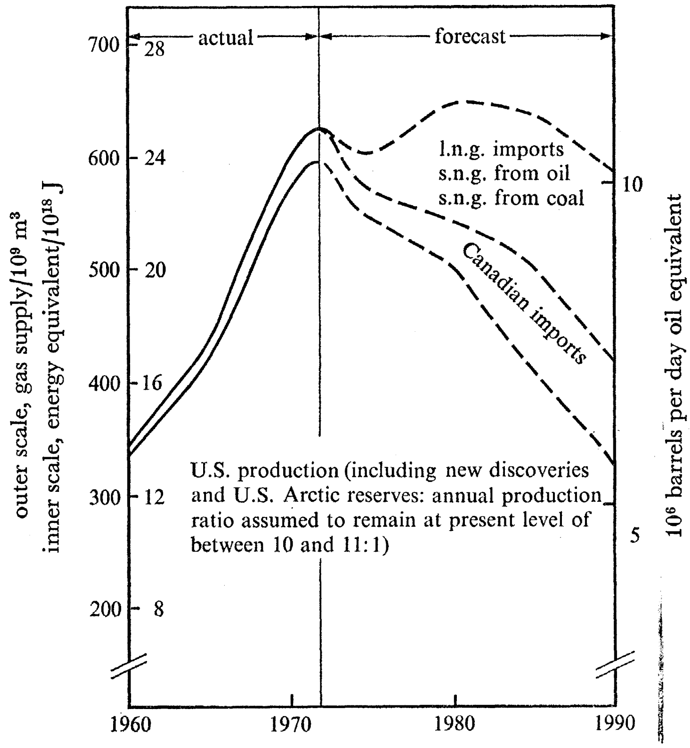

FIGURE 5. U.S. gas supplies – actual and forecast availability.

6. THE U.S.S.R.

In spite of the somewhat limited published data available, it is widely recognized that the U.S.S.R. has a natural gas resource base greatly in excess of its very large existing and future internal needs. Figure 6 shows how the contribution of natural gas to the U.S.S.R.'s energy consumption has grown from about 4 % in 1950 to a healthy 24 % by 1972 and is expected to continue growing both in absolute terms and percentage contribution through the 1970s.

Figure 1 indicated that current proven gas reserves in the U.S.S.R. are around 18×10^{12} m^3 or about one-third of the best estimate of total world gas reserves. However, prospective U.S.S.R. reserves could be considerably greater. For example, a paper presented by a Soviet delegate to the 12th World Gas Conference at Nice in June 1973 (as also in other papers to various international bodies) indicated that prospective reserves, located at depths of less than 4500 m, could amount to 86×10^{12} m^3, of which one-half are in West Siberia including the Tyumen area (see table 1 for details).

How much of these prospective reserves can be proved, developed and brought to market must be a matter for conjecture. The problems of drilling and constructing the necessary pipeline systems in areas such as Tyumen, which are not only remote from the market and from suitable export points, but which also have climatic and topographical conditions which are among the most severe to be found in the world, are formidable by any standards.

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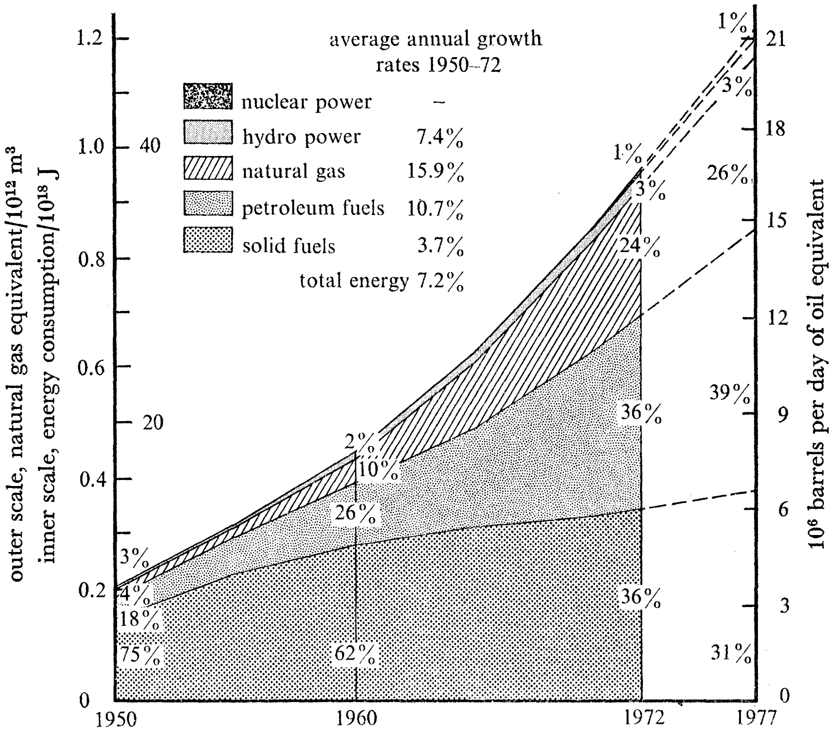

FIGURE 6. U.S.S.R. – energy consumption and forecast, 1950–77.

TABLE 1. GEOGRAPHIC DISTRIBUTION OF U.S.S.R.'S PROSPECTIVE GAS RESERVES

location	less than 4500 m		4500–7000 m	
	10^{12} m^3	%	10^{12} m^3	%
European U.S.S.R. (including Komi and Oldenburg)	15.0	17.4	5.6	56
west Siberia (including Tyumen)	42.3	49.2	0.2	2
east Siberia (including Sakhalin and Yakut)	15.7	18.3	–	–
middle Asia and Kasakhstan (including Turkmenian)	13.0	15.1	4.2	42
total U.S.S.R.	86.0	100	10.0	100

However, during the last few years the U.S.S.R. has undertaken long-term export commitments to supply natural gas by overland pipeline to Austria, Finland, France, Italy and West Germany, as well as to various East European countries, and negotiations are reported to be well advanced for possible supplies to Sweden. Gas to meet these commitments will come largely from existing fields in reasonably accessible locations that are either close to or already linked with the existing pipeline network. Even so this network does not have sufficient capacity to handle all these commitments and most of the U.S.S.R.'s gas deals so far have involved the reciprocal supply of high-pressure, large-diameter steel line-pipe.

More recently serious interest has been shown by various American gas companies, supported by the U.S. government, in the possible export of Soviet l.n.g. to both the U.S. east and west coasts. These export possibilities would require the development of west Siberian reserves in the case of supplies to the U.S. east coast and east Siberian reserves for the U.S. west coast. In addition to the massive capital investment required for liquefaction plants and l.n.g. ships, such exports would necessitate a large appraisal and development drilling programme, and the construction of new pipeline systems over long distances to suitable year-round ice-free export ports. The realization of these plans must depend upon the continuing political desire of both the American and Soviet governments to establish closer trading links between the two countries; if this is maintained, it can be assumed that the technological strength of the American and Soviet gas industries will surmount the practical problems. Even under the most favourable conditions, however, it will obviously be some years before such exports can actually start.

Whatever discount factor may be applied to the announced Soviet expectations of future gas reserves, the U.S.S.R. does and will have the necessary resource base to fulfil its present export commitments and to undertake substantially greater ones. Soviet gas is and will remain a most important factor in the world scene.

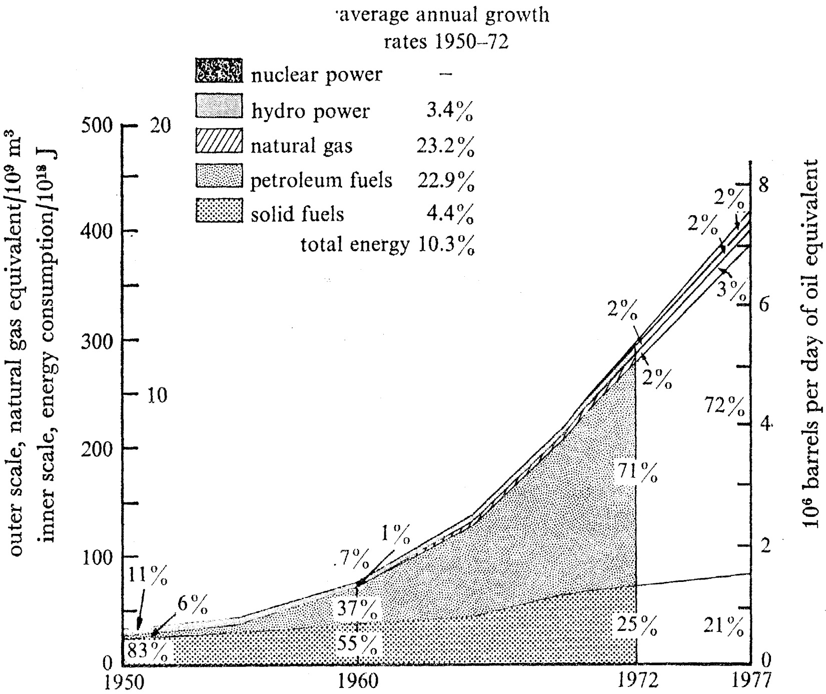

FIGURE 7. Japan – inland energy (excluding ships' bunkers and international aviation), consumption and forecast 1950–77.

7. JAPAN

The growth in energy consumption in Japan over the last 15 years or so has been quite remarkable by any standards, with total energy consumption rising from less than 2×10^{18} J (50×10^9 m^3 of natural gas equivalent) in the mid-1950s to about 12×10^{18} J (300×10^9 m^3) in 1972 (see figure 7).

This represents an average annual growth rate of over 10 % in total energy consumption and is the highest growth achieved by any industrialized country in the world. In the same period there have also been some radical changes in the energy supply pattern. For example, whereas in the mid-1950s coal supplied around 70 % of total energy consumption and oil little more than 20 %, by 1972 the percentage contribution of these two main primary forms of energy had been almost exactly reversed.

Japan has only very small indigenous reserves of natural gas and as can be seen from figure 7 natural gas's contribution to this growth in energy consumption was negligible. Natural gas represented barely 1 % of primary energy consumption in the 1960s and only about 2 % in 1972. It is possible, of course, that further reserves of natural gas may be discovered in the new exploration area now being explored offshore Japan, but in the absence of any such commercial discoveries, Japan must rely upon imports or s.n.g. if the gas market is to expand. Indeed the practice of importing natural gas in liquefied form is already well established. Since 1969 Japan has been importing 1.5×10^9 m^3/year of gas in the form of l.n.g. from Alaska (the Phillips/Marathon project) and this was followed in December 1972 by the start of imports from Brunei (the Shell/Mitsubishi/Brunei Government project) in quantities which will rise to about 7×10^9 m^3/year by the mid-1970s. These two l.n.g. schemes, together with the existing local production, will enable natural gas to supply about 3 % of Japan's growing total energy demand by the late 1970s.

What then are the further prospects for natural gas utilization in Japan? First, the energy requirements of Japan are so large that virtually any quantities of gas (or oil) that may be discovered on land and/or offshore Japan would be readily absorbed by the market, bearing in mind the time it would take to develop such new reserves. As Japan relies on imported energy to meet well over 80 % of its total requirements any indigenous supplies would help to reduce the country's dependence on foreign sources of supply in a world where oil availability is expected to become increasingly tighter. Secondly, Japan has a pressing need for clean energy to alleviate the very severe problems it is now experiencing as a consequence of its rapid industrial expansion and the concomitant increase in the standard of living and purchasing power of its population. Thirdly, based on the small indigenous supplies of natural gas and the existing imports from Alaska and Brunei, some of the gas distribution companies are converting or planning to convert their existing low-energy high-cost manufactured gas systems to high-energy natural gas. Over time this will improve their distribution economics and enable these companies to penetrate the space heating and other large-volume marketing outlets. Coupled with this is the increasing use of natural gas for industrial applications and for power generation either for reasons of fuel efficiency, for economic considerations or to reduce air pollution.

The above and other related factors all tend to encourage the demand for natural gas. In the absence of substantial indigenous supplies this demand can only be met by further imports of l.n.g., supplemented by high-energy s.n.g. from, initially, oil feedstocks, and possibly by the 1980s from coal. The prospects for natural gas in the longer term are thus more likely to be constrained by supply availability than by demand limitations.

What sources of supply are likely to be developed to meet this increasing demand for gas? While the delivered price of l.n.g. imports will always of course be an important factor, the continued rising prices of alternative competitive energy forms such as low sulphur oil are steadily increasing the economic radius of l.n.g. schemes. For supply security reasons, Japan will also probably wish to draw its future gas supplies from the widest possible variety of geographic and political sources, even if this incurs some economic disadvantage. The most probable supply sources at the present time (in no special order of timing or of exportable potential) are Malaysia, Indonesia, the U.S.S.R., and various countries in the Middle East (e.g. Abu Dhabi, Iran, Qatar, etc.). Australia must be excluded from this list because of the present government's policy of non-export. Figure 8 shows the geographic relationship of these potential supply sources, and some others such as Bangladesh, to Japan and also to the U.S. west coast, which could be an alternative outlet for some of these supplies.

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It is clear that, bearing in mind the 'cost of distance', the Middle East is less favourably placed than other potential sources, but for the reasons mentioned above this prolific gas-bearing region is nevertheless likely to become a substantial supplier of gas to Japan. A combined l.n.g. gas liquids scheme from offshore Abu Dhabi has already reached the firm contract stage and others will no doubt follow.

FIGURE 8. Principal natural gas reserves in relation to Japan and U.S. west coast. (1 km ≈ 0.54 nautical miles.)

Based on present technology, expected capital and operating costs, distance from market, etc., and allowing for the effects of inflation, the laid-down price in Japan of l.n.g. by the early 1980s could well be in the U.S.¢114–142/10^9 J range (¢120–150/10^6 Btu). This price range is not thought to be unrealistic or unduly out of line with the price of alternative forms of clean energy that are likely to prevail at that time.

By the mid-1980s Japan is likely to be importing from between 30×10^9 and 60×10^9 m^3/year of gas in the form of l.n.g., the exact level depending on how quickly the market adjusts itself to absorb l.n.g. and the rate at which new projects can be negotiated, built and brought on-stream. To achieve this range of imports will require a very substantial effort by the industry and the governments concerned if it is to be realized over a time-span of barely 10 years. However, even at the higher level of l.n.g. imports postulated, natural gas would be supplying only about 5 % of Japan's total energy demand in the mid-1980s. Like the U.S.A., but unlike the U.S.S.R., the growth for gas in Japan will be constrained by supply availability rather than demand potential in the foreseeable future.

8. WESTERN EUROPE

Figure 9 gives a broad impression of the relative size and location of the main gas reserves in Western Europe, as published by the *Oil and gas journal* (December 1972). It shows that the major deposits so far found in Europe have been in the Netherlands and in the North Sea, to which should be added the smaller but nevertheless important reserves in West Germany,

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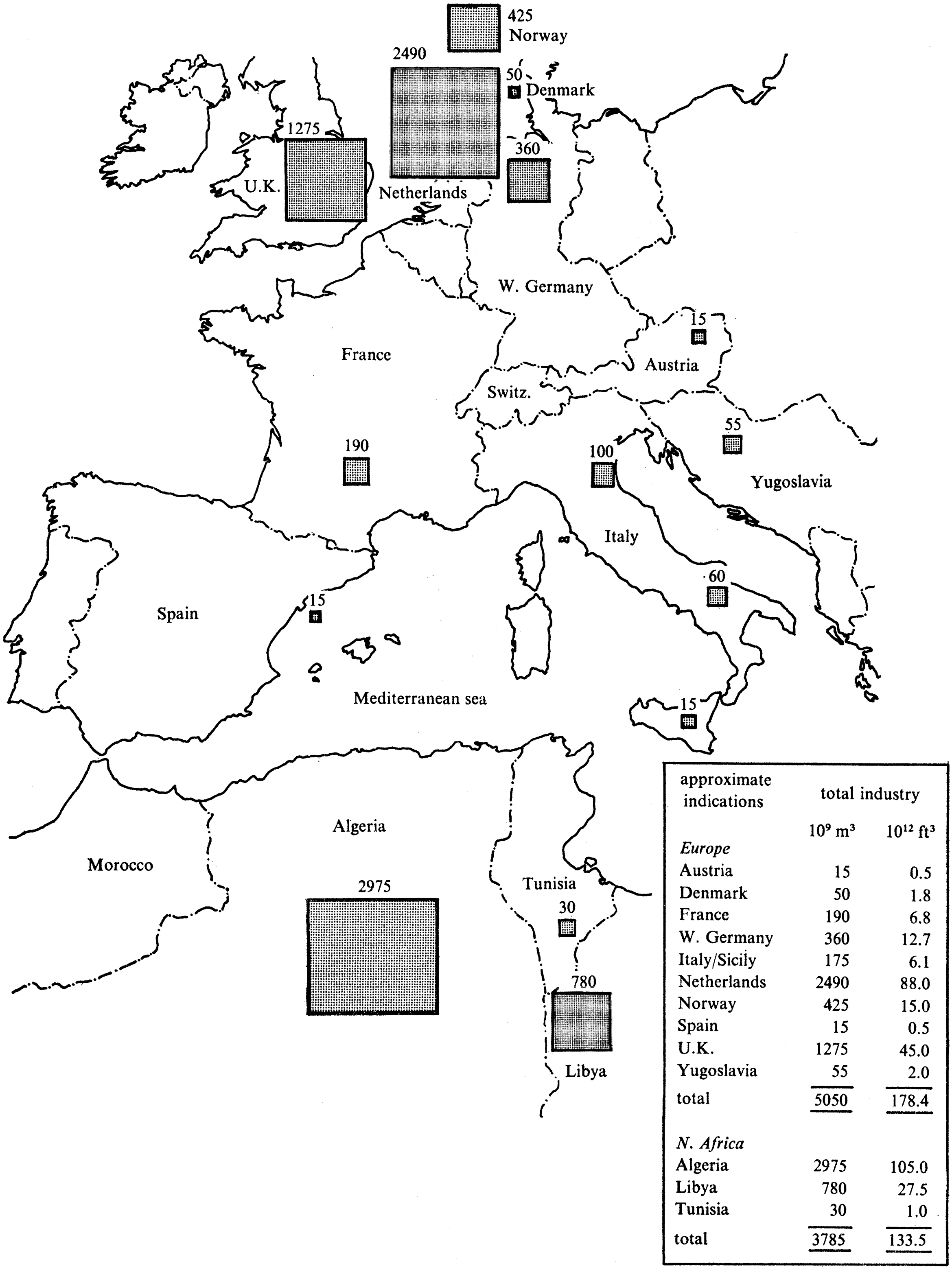

approximate indications	total industry 10^9 m³	total industry 10^{12} ft³
Europe		
Austria	15	0.5
Denmark	50	1.8
France	190	6.8
W. Germany	360	12.7
Italy/Sicily	175	6.1
Netherlands	2490	88.0
Norway	425	15.0
Spain	15	0.5
U.K.	1275	45.0
Yugoslavia	55	2.0
total	5050	178.4
N. Africa		
Algeria	2975	105.0
Libya	780	27.5
Tunisia	30	1.0
total	3785	133.5

FIGURE 9. Estimated natural gas reserves in 1972. Western Europe and North Africa – 10^9 m³ (source of data, *Oil and gas journal*, December 1972).

France and Italy. Algerian reserves are also shown on figure 9 as, like Soviet gas, these reserves could have a significant role to play in Europe's future gas supply picture. The figures for Norwegian reserves shown are in fact almost certainly now on the low side, bearing in mind recent discoveries.

The historical development of the natural gas market in Europe is well documented and it is not proposed to give a detailed account in this paper. The European gas industry is now fully committed to natural gas with conversion from manufactured gas to natural gas complete or virtually complete in the Netherlands, Belgium, France and Italy and well advanced in the U.K. and West Germany.

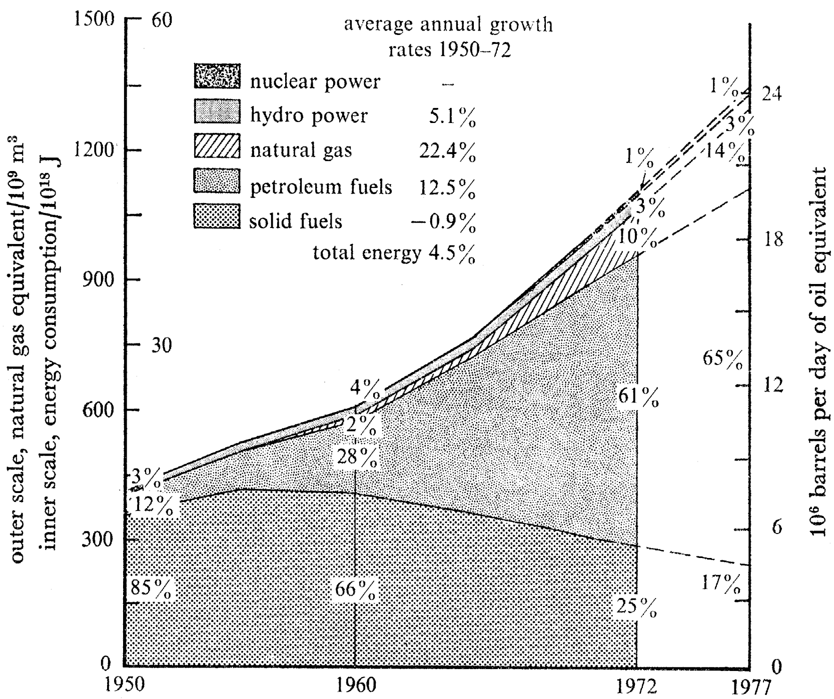

FIGURE 10. Western Europe – inland energy (excluding ship's bunkers and international aviation) consumption and forecast 1950–77.

Consumption of natural gas has exceeded most previous predictions. Between 1969 and 1972, despite generally mild winters, natural gas consumption in Western Europe as a whole increased by an average annual rate of 30 % compared with only a 5–6 % annual increase for total energy over the same period. Figure 10 shows how natural gas has grown from about 2 % of total energy consumption in 1960 to 10 % by 1972 and is forecast to increase to 14 % by 1977 reaching 15 % shortly thereafter.

Although figure 10 gives a general indication of energy developments in Europe, it does conceal substantial variations within individual countries, as is shown by figure 11, which gives an estimate of primary energy consumption in 1977 in the seven main markets for gas in Europe.

Whereas in terms of percentage of primary energy consumption, the largest market for gas will be the Netherlands, where gas is expected to supply some 60 % of primary energy consumption in the late 1970s, West Germany with about 16 % for gas and the U.K. with around 18 % are both larger gas markets in terms of quantity.

Existing indigenous reserves supplemented by established and firmly contracted imports of pipeline gas from the U.S.S.R. and l.n.g. from Algeria will, as already indicated, enable natural gas to supply about 15% of West European energy by the late 1970s, by which time all the presently known main gas fields are expected to be on or near plateau production levels. In the absence of major new discoveries and/or further imports, natural gas will inevitably steadily decline thereafter in the contribution it can make to total energy supply. While this is the overall situation for Europe in the longer term, some limited gas supply shortages are already beginning to be felt in certain localized areas in West Germany, France, Italy and Belgium; by the late 1970s a similar situation can be expected for the U.K. Some of these immediate supply deficits will be filled by gas from recent discoveries in the North Sea for which contracts have been concluded but where the pipeline system from gas fields to the mainland has yet to be built (e.g. Ekofisk and Frigg) or in some cases which have yet to be firmly committed (e.g. Brent). Also some additional imports of l.n.g. from Algeria are currently being negotiated. However, these new identifiable supplies are only likely to push the supply shortage back a few years.

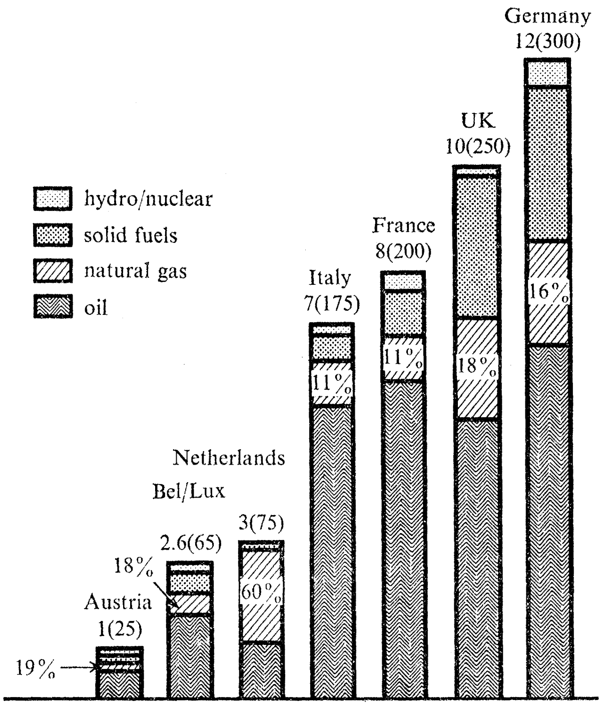

FIGURE 11. Estimated primary energy consumption in 1977 – 10^{18} J (10^9 m^3 of natural gas equivalent).

What then is the future for gas in Europe? Will total gas supply level off in the late 1970s or can the gas industry continue to grow? The market pressures for growth in gas, already strong will no doubt intensify. By the late 1970s virtually all Europe's gas distribution systems will have been converted from manufactured gas to natural gas. Other energy forms, in particular oil, are expected to be in short supply. Environmental pressures, which favour the use of a clean fuel such as natural gas, will increase. Increasing prosperity and the concomitant desire for better living standards will enhance the demand for gas for space heating and similar 'desirable' applications. All these and other related factors will raise the demand for gas within the present inter-fuel price relationship. In an unrestricted supply situation it is entirely reasonable to suppose that natural gas could take up a third or more of Europe's energy demand. But can it in practice? The answer is, most probably, no, because even under the most optimistic assumptions the market is likely to remain supply-restricted.

What are the prospects for new supplies? First and foremost will be the development of such new reserves as may be discovered in and around Europe. The European offshore, in particular, is still a relatively new petroleum exploration area. Most of the early discoveries were of gas and now the pendulum is swinging towards oil, but nobody can forecast with any degree of precision what new exploration will offer in future – oil, gas, both or nothing. All one can conjecture is that with many new areas such as the Western Approaches, the Irish and Celtic seas, and large parts of the North Sea, the Adriatic and the Mediterranean yet to be explored, surely more gas reserves will become available in the years ahead. However, it would take an optimist to assume that the industry will discover the equivalent of an additional Groningen or several Leman Bank gas fields which would be necessary if natural gas were to achieve a substantial increase in its share of future European energy consumption.

Secondly, further imports of pipeline gas from the U.S.S.R. and l.n.g. imports from Algeria are probable. Although as already discussed the potential reserves in the U.S.S.R. in particular are very considerable, most of the readily exploitable reserves in these two countries appear to be already committed to various markets and it would seem that a breathing space is now likely in which they can build facilities to fulfil their commitments and appraise their undeveloped potential reserves before embarking on a 'second round' of export commitments. Most probably they will have more gas to offer in the years ahead but it appears unlikely that this second phase of commitment could make any worth-while contribution to Europe's gas supply picture much before the 1980s.

Thirdly, s.n.g. from oil or coal will probably have a role to play, but European coal is not cheap and oil prices are moving upwards. s.n.g. is likely to be very expensive and possibly limited in the contribution it can make.

Fourthly, l.n.g. imports from farther afield than Algeria, such as from West Africa and the Middle East, may well be arranged in the years ahead, but, like s.n.g., such l.n.g. supplies will be expensive as a consequence of the long shipping distances and consequent high freight costs.

Lastly, there is the possibility that gas may be brought to Europe by large-diameter pipeline from the Middle East, either by direct delivery – for example, through Turkey, Greece and Yugoslavia – or by exchange as in the recently announced project between Iran, the U.S.S.R. and West Germany. The cost would be high and there are likely to be political problems, but nevertheless such schemes may well play a part in the European supply pattern in the 1980s.

The complexities of these various new and supplementary sources of gas are such that any long-term forecast becomes so highly speculative and wide-ranging as to have little practical meaning. Nevertheless, and in spite of these reservations, sufficient new supplies should be forthcoming to maintain some growth for the European gas business through the 1980s and perhaps for some time thereafter, although probably not to the extent that all market opportunities for gas can be taken up in all the main European markets of interest. This supply constraint will mean that gas distribution companies in Europe, as now in the U.S.A., will become increasingly selective and will concentrate supplies upon those outlets (domestic and premium industrial) which can support higher cost gas and where gas has special economic, social and environmental advantages over other fuels.

9. Other possible supply systems

So far the paper has discussed the role that s.n.g. from coal or oil and l.n.g. imports may play in the future in supplementing indigenous supplies of natural gas. S.n.g. from oil and l.n.g. are proven and s.n.g. from coal is confidently expected to begin to make its contribution by the end of this decade. What other possibilities are in prospect?

Appreciable publicity has been given of late to the conversion of natural gas to methanol (or methyl fuel), which as a liquid product could be shipped much more cheaply than l.n.g. In the receiving country the methanol could either be re-formed to pipeline-quality natural gas, or it could be used directly as a low-pollutant fuel for industrial application. Manufacturing methanol from natural gas is substantially more expensive than the gas liquefaction process but, because cheaper ships can be used, the methanol conversion route may offer an overall economic advantage over an l.n.g. system in cases where very long ocean transportation distances are involved – for example, from the Middle East to the United States. With the increasing attention that is being paid to the exploitation of natural gas from such distant sources, some commercial projects for manufacturing and shipping methanol are being actively investigated and may materialize in the years ahead.

An approach which attracts by its theoretical elegance but which has not yet found practical application is that of the 'cold carrier' system. Work has been carried out upon various such systems, in which the cold arising from the re-gasification of l.n.g. in the country of receipt is transported back to the gas-producing country in order to reduce liquefaction costs. If such a system were to prove competitive with conventional l.n.g. shipments, this would be particularly over short ocean distances (for example, across the Mediterranean). With further technological development, and improved economics, such systems may yet have a role to play.

In the past a number of gas transportation systems using different combinations of low temperatures and high pressures have been studied, but so far nothing has been found to compete with the by-now conventional l.n.g. system, in which the natural gas is kept at or below its boiling point at virtually ambient pressure.

Very large rigid airships each capable of transporting, say, 3×10^6 m^3 (1×10^8 ft^3) of natural gas in the gaseous state are another possible method of transport. This idea is at present in the preliminary evaluation stage but may in time prove a viable alternative to l.n.g., particularly over shorter distances (say, less than 3200 km) and in this event would bring a new flexibility to gas transportation. Because of the necessary development time, it is improbable that such airships could become a commercial proposition before the mid-1980s.

The profitable utilization of the cold released when l.n.g. is re-gasified in the reception terminal is an area which offers obvious scope for improving the economies of l.n.g. schemes. Although a variety of technically valid applications for this cold exist, e.g. ethylene manufacture, the food industry, air separation, desalination, etc., such applications do not make a substantial financial contribution in any of the existing or announced l.n.g. projects. The reason for this seems to be commercial complexity rather than technical difficulty; as more l.n.g. projects come into operation it is certain that schemes to make use of the cold available at the receiving terminals will be developed.

Finally, a long-term prospect which does not involve natural gas as such but which may be considered to fall within the scope of this paper since it would make use of existing natural-gas transportation and distribution pipeline systems, is the so-called 'hydrogen economy' concept, in which hydrogen produced with the aid of nuclear energy (either via electricity generation followed by the electrolysis of water, or by a combined nuclear heat/chemical process) is fed into a pipeline system and distributed for the same sort of applications as natural gas. The interest aroused by this concept is due to the fact that it offers an attractive alternative to total electrification of the world's economy at that time in the future when nuclear power generation becomes the principal source of energy. Advantages claimed for it, compared with electricity, include:

(i) transmission and distribution of energy more efficiently and at lower cost;

(ii) less disfigurement of the environment;

(iii) easier storage;

(iv) potential for use as a hydrocarbon fuel component, as a chemical feedstock and as a feedstock for fuel cells.

However, a development along these lines is unlikely to become a significant factor in world energy supplies until the cheaper recoverable fossil fuels are nearing exhaustion and nuclear generating capacity is available on a massive scale. It therefore almost certainly falls outside the period under discussion in this forum.

10. Conclusion

World resources of natural gas are theoretically more than sufficient to match world demand. However, for economic, geographical, logistic, political and other reasons, supply shortages are already apparent in the United States and are beginning to emerge in Western Europe.

Gas which can be transported to market by pipeline is, and will remain, the mainstay for the continuing development of most natural gas markets. L.n.g. imports and s.n.g. are, or will become, useful and important sources of supply, but their role will usually be to supplement and not to replace pipeline gas. The notable exception to this is Japan, where l.n.g. imports, in the absence so far of any indications of worth-while indigenous energy supplies, will almost certainly provide the base source of supply for future development of the Japanese gas market.

'Cost of distance', in spite of a growing world-wide appreciation of an energy shortage, is likely to remain an inhibiting factor in matching potential sources of gas with potential demand. Less immediately apparent but possibly of even greater inhibiting effect is the fact that, even where the theoretical economics of an international l.n.g. project appear technically and financially viable, the complex problem of reaching agreement on the intricate political, fiscal and commercial aspects of the venture (which may involve capital expenditure well in excess of U.S. $\$1 \times 10^9$) may be such as to outweigh all else as a factor for delay, possibly causing years to be lost or even (in extreme cases) the complete missing of a market opportunity.

In a number of markets natural gas prices have been either arbitrarily regulated or otherwise linked to the cost of relatively low-value alternative energy forms. This has resulted in the expansion of the use of gas for inferior purposes such as steam-raising, where other fuels would have been more suitable. Prices for natural gas in such markets will probably move upwards in the future to equate with the true market value appropriate for this clean, versatile and flexible form of energy. This will help to ensure that natural gas is economically employed in those applications and market sectors where its inherent qualities can be utilized to the maximum advantage, and at the same time will provide added encouragement and incentive for the search for and development of new prospective gas-bearing areas.

The task which lies before the gas industry is:

(1) To press ahead with the full and proper exploitation in the market-place of existing and prospective gas reserves located in or close to the main markets.

(2) To attack the problem of linking distant gas sources to markets by continuing the development of supply systems based on l.n.g., large-diameter pipelines or whatever other methods may prove competitive.

(3) To establish and foster with governments a clear understanding of the problems and opportunities so that complex projects based upon such systems may come into operation without undue delay.

(4) To sponsor research into and development of all other economic forms of supplementary gas supplies such as synthetic natural gas from oil and coal, conversion of natural gas to methanol (where this offers advantages over l.n.g.) and any other new processes or systems which can contribute to the supply pattern.

In this manner the distinctively valuable contribution made by gas to meeting the world's ever-expanding need for energy can be maintained and reinforced.

Discussion

Dr W. C. Marshall, F.R.S. (*A.E.R.E. Harwell, Didcot, Berkshire*)

Once we have the pipelines and infrastructure of a gas industry, I can see the argument for converting coal to 'synthetic natural gas', but in the long run it is not wiser to think primarily in terms of converting coal to a synthetic crude oil, because the latter process would make less demands upon a hydrogen supply?

Mr Coppack's reply was to agree with this comment but to stress that the infrastructure of a gas distribution system would, in practice, argue strongly for a significant conversion of coal to synthetic natural gas indefinitely.