A framework for natural gas planning

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FOR MANY of the developing countries, indigenous natural gas resources hold the key to reducing an expensive reliance on oil. Yet in many cases, the current level of gas use is low relative to the reserve base and to an economically desirable level. Embarking upon the development of natural gas — a non-renewable fuel and one which requires large, up-front investments to transport and use — raises complex questions of gas allocation and investment strategy that must be faced at the pre-investment stage of development.

Many of the questions are similar across countries, for example:

- Should gas be used in electricity generation in preference to imported coal, or should a gas-based fertilizer plant be built to replace imported urea?
- Would the high cost of a city gas distribution network be justified by the very high and growing cost of the kerosene and LPG used by households that gas could replace?
- If gas reserves are large, should the country try to attract commercial partners for an LNG export project, or — with today's lower price projections — would it be better to keep the gas in the ground to satisfy future domestic needs?

Such questions are essentially economic rather than technical. The technical feasibility of using gas for power generation, for fertilizer production, for LNG, and so forth, has been well-proven and need not be established anew. The important issue is the relative economic merit of the different alternatives. This will depend upon such country-specific parameters as the amount of base-load hydro in the power system, the proximity to major export/import markets for urea and the density of housing in urban areas.

To answer questions such as the above, a long-run, sector-wide analytical framework is needed, which takes explicit account of the economic

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linkages involved between gas costs, benefits, prices and alternative depletion policies. A piecemeal approach to evaluating individual projects, one at a time, will not usually be appropriate. Economies of scale can often be exploited to reduce costs by careful selection and timing of gas-using and gas-producing projects. As in the power sector, a long-run multi-project framework is needed to identify those investments which make up the least-cost expansion plan.

An additional complication in gas sector planning is accounting for the cost of depletion — that is, the cost of future consumption foregone by using the resource today. This can only be calculated by estimating the time path of future consumption. The fundamental planning problem for natural gas is that the economic price of gas is itself a function of the set of projects selected. Thus a long-run, iterative framework is needed to arrive at the gas development programme that maximizes the social welfare of the country involved.

This paper aims to present such a framework. To keep the exposition uncluttered, simplifying assumptions are used and graphical illustrations present both time snapshots and trends over time, holding price or other variables constant. We do not consider the non-economic costs and benefits of gas development (e.g. environmental risks, regional development benefits), which may be significant in some countries. Further, we subsume many of the technical questions involved in defining a stable production plateau or in allocating costs between gas and oil when they are produced as joint products. We deal only briefly with the problem of uncertainty in estimating the parameters needed.[1] Thus, while this framework is a comprehensive one, it would need to be refined and extended to suit the particular circumstances of any one country.

Natural gas demand

The demand function for gas relates the quantity of gas demanded at various prices at a given point in time. At any time, t, the quantity demanded, Q_t^D, will depend upon the price of gas at that time, P_t, the prices of relevant substitutes and complements (e.g. fuel oil and fertilizers) and income variables such as the level of GDP or the world demand for methanol. For simplicity, in the equation which follows, these income variables are lumped together into an aggregate trend variable, Y_t. The equations are further simplified by assuming that the only relevant non-gas price is that of fuel oil, which is assumed to be constant over the period and equal to $4 per million Btu (mBtu).

With these assumptions, the demand equations for gas can be represented as follows:

$$Q_t^D = f(P_t, Y_t) \qquad \text{for } P_t \leqslant 4$$

$$Q_t^D = 0 \qquad \text{for } P_t > 4$$

Figure 1(a) shows the demand function for a particular level of Y. Above the level of $P = 4$, the demand for gas falls to zero as all users in this simplified example shift to fuel oil. **Figure 1(b)** shows the growth of gas demand over time at two different (constant) price levels.

Natural gas supply

On the supply side, an analogous distinction must be made between the relationship of costs to the quantity of gas supplied at any point in time and the trend of gas supply over time at assumed prices. The first of these is the supply function for gas. At any time, t, the quantity supplied, Q_t^S, will depend upon the price of gas, P_t, and the technical parameters governing production. In addition, the supply function for a depletable resource has a special constraint to reflect the fixed nature of total production over time.

For simplicity, we assume that production costs are constant at \$1/mBtu, and that production rates are not a function of the price unless it falls below the cost of production, in which case no gas is supplied by the producers.[2] The technical parameters affecting the pace at which gas production can be expanded, and the rate at which production declines from reservoirs can be expected, are again lumped together into a trend variable, X_t, for simplicity. They are also defined with reference to a maximum production scenario, Q^{max}, which represents the fastest, technically appropriate gas development programme based on total reserves of R.

Given these assumptions, the quantity of gas supplied at time t can be described as follows:

$$Q_t^S \leqslant Q_t^{max} \qquad \text{for } P_t \geqslant 1$$

$$Q_t^S = 0 \qquad \text{for } P_t < 1$$

$$Q_t^{max} = g(X_t, R)$$

$$\sum_{t=0}^{T^e} Q_t^S \leqslant R \qquad \text{where } T^e \text{ denotes the point of exhaustion.}$$

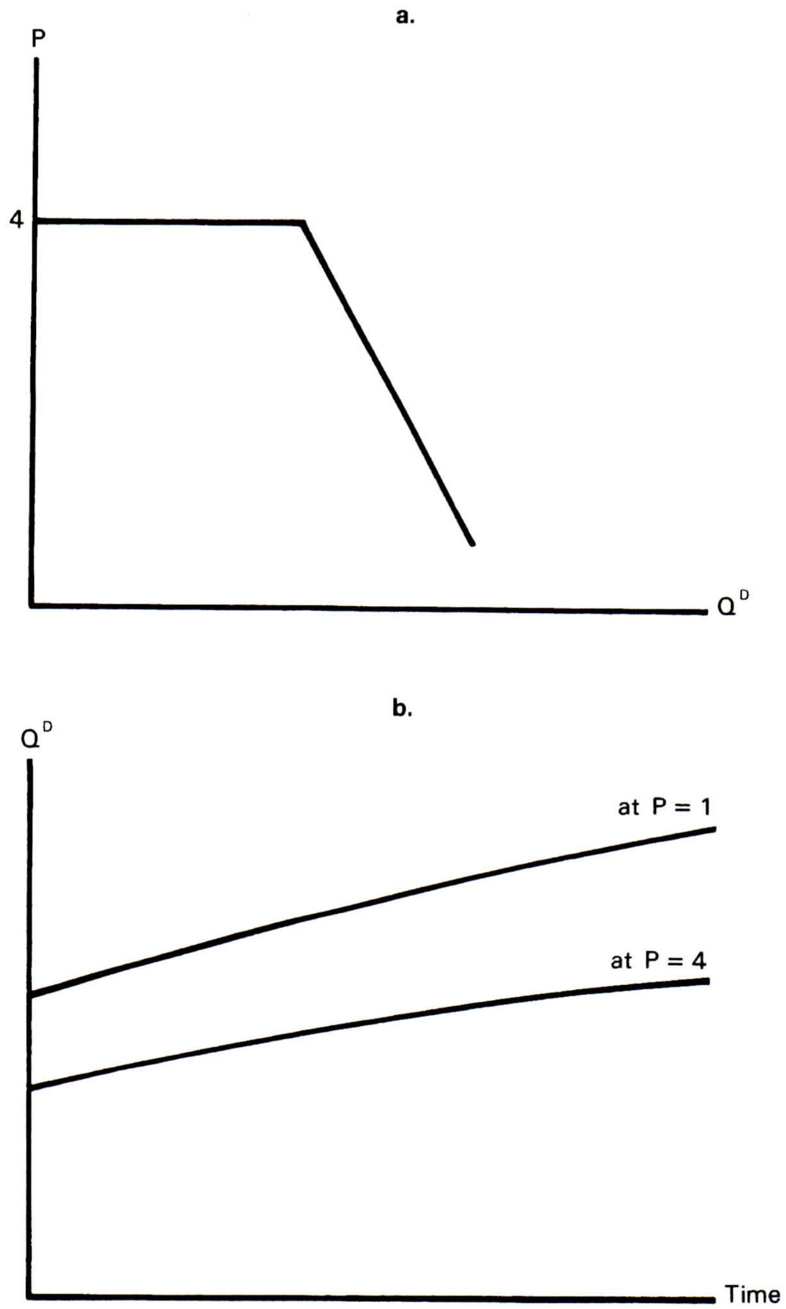


Figure 1
The demand functions for gas

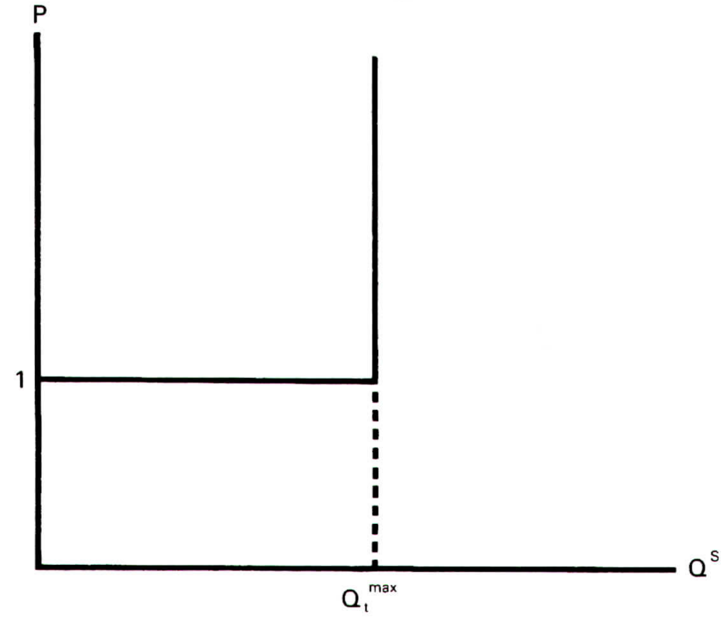
Figure 2(a) shows the supply function described by these equations for a particular level of X (i.e. a particular point in time), while **figure 2(b)** shows the maximum supply curve over time. Given our simplifying assumptions, no gas is produced if the price falls below \$1/mBtu, and above that level production will depend on demand, but cannot exceed Q_t^{max}. The final constraint in the set of equations above ensures that no alternative supply curve over time can enclose an area larger than that enclosed by Q^{max}, as shown in figure 2(b).

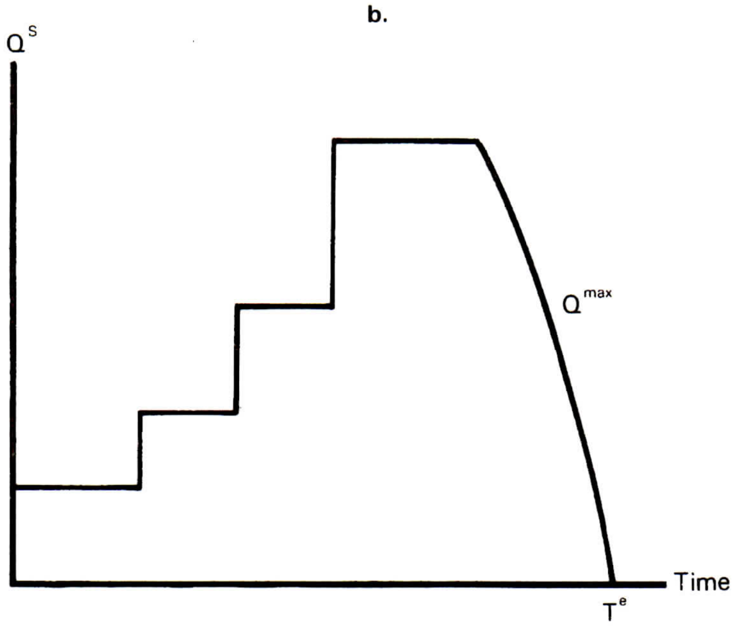
Natural gas price

The final equation set needed to complete the system concerns the price of gas. In the general case, the price of a depletable resource will contain two components: the cost of extraction (here assumed to be a constant \$1/mBtu) and the depletion premium, V_t, which can also be thought of as the shadow price of the reserve constraint. The fundamental principle of depletable resource economics (also called the Hotelling principle) is that,

Figure 2
The supply functions for gas

a.





under equilibrium conditions, the depletion premium must increase over time at a rate equal to the opportunity cost of capital, r. As the price of the resource grows over time, the demand for it naturally falls (other things remaining equal), so that the resource is just exhausted as the price has risen so high that the demand has fallen to zero.[3]

In this example, the demand for gas falls to zero when its price reaches the cost of its importable substitute (i.e. fuel oil at $4/mBtu equivalent), thereby placing an effective limit on V_t. Such a limit also provides the critical end point from which earlier V_t can be derived using the Hotelling principle, as illustrated here.

The lumpiness and long lead times of investment in the gas infrastructure often result in periods of supply constraint, where production is limited not by gas reserves but by the investment needed to produce and deliver the gas to consumers. This limit creates the steps in the early part of the Q^{max} curve shown in figure 2(b). If the demand for gas is greater than Q^{max} during these early periods, then the economic price of gas will include an element representing the scarcity rent of capacity (i.e. the shadow price of the supply constraint), C_t, during those periods when production is limited by the available infrastructure. Note, however, that C_t is limited by the price of the gas substitutes and, in our example, cannot exceed $3/mBtu.

Where Q_t denotes the quantity of gas consumed at time t, the set of price equations will be as follows:

$P_t = 1 + V_t + C_t$

$V_t + C_t = 3$ for $Q_t = Q_t^{max}$

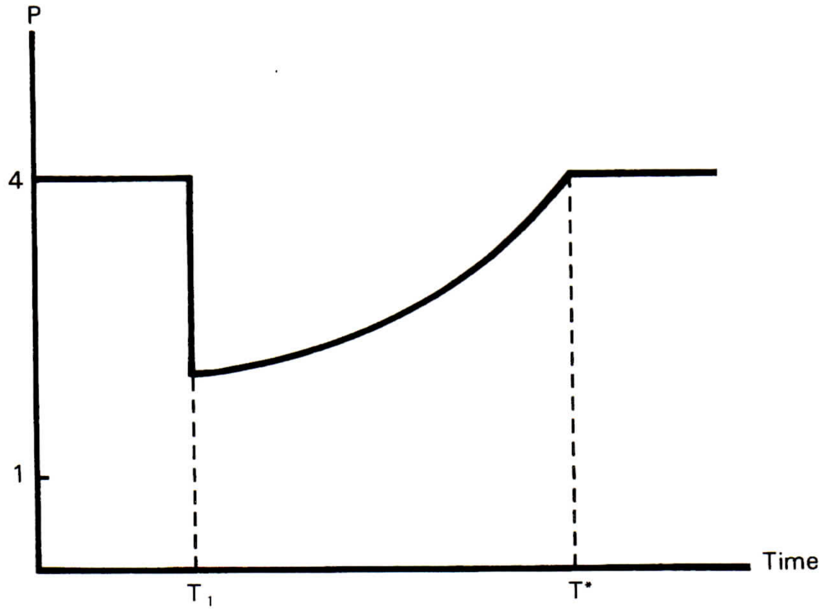
$V_t = 3[1/(1 + r)^i]$ for $Q_t < Q_t^{max}$

$C_t = 0$ for $Q_t < Q_t^{max}$

where $i = T^* - t$ and T^* is the date at which $(Q^D - Q^S)$ switches from negative to positive.

Figure 3 illustrates a typical price path described by the equations above. During the early years ($t < T_1$), when gas consumption is constrained by infrastructure development, the rental element of the gas price ($V_t + C_t$) is equal to its maximum value of 3, and the economic price of gas is

Figure 3
The price path of gas



equivalent to that of its marginal replacement, fuel oil. Then, in the years between T_1 and T^*, the potential gas production has caught up with demand, so that $C = 0$ and the depletion premium is less than 3. During this period, the depletion premium approaches its full value of 3 at the rate r. At T^*, when $V_t = 3$, potential demand again exceeds supply at a total price of $4/mBtu.

For a numerical example, assume that domestic gas reserves are such that demand will exceed supply after 1996, when fuel oil will again have to make up the gap. In that year, the depletion premium for gas will be its replacement value less its production cost, or $3/mBtu. If the opportunity cost of capital for this country is ten per cent, then the depletion value of gas in 1986 is the present value of $3 ten years hence, or $1.2. With the assumption of constant gas costs, this implies that the economic price of gas in 1986 is $2.2/mBtu (= 1 + 1.2). By 1990, this price will have risen to $3 (= 1 + 2.0), and by 1996 to $4.

An iterative solution process

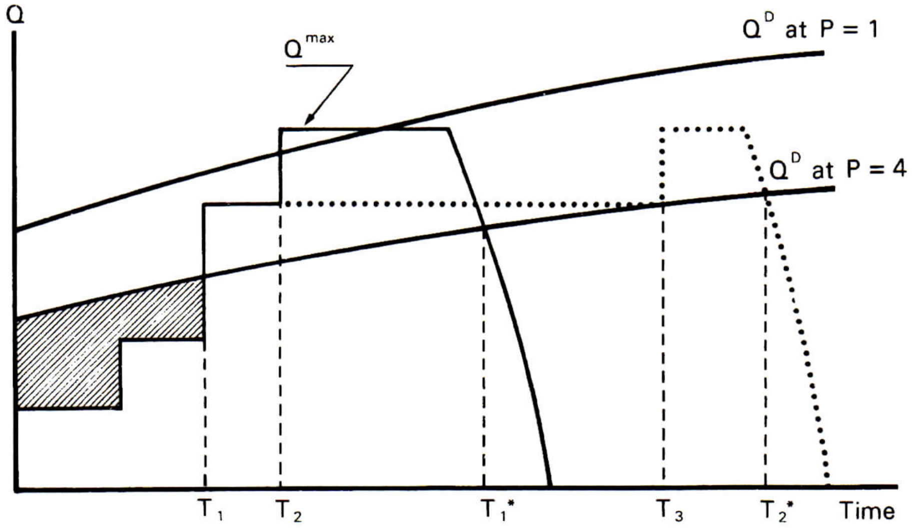
The solution to the sets of demand, supply and price equations can be illustrated graphically using an iterative process. Trial 1 consists of superimposing the time-variant demand curves of figure 1(b) onto the maximum supply curve of figure 2(b). The two demand curves shown for $P = 1$ and $P = 4$ represent the limits of potentially relevant demand, since either supply or demand will be choked off if the price of gas falls below its cost of production or rises above the price of substitutes.

As shown in **figure 4**, from year 0 until T_1, the consumption of gas is constrained by supply (Q^{max}), with the country continuing to use the amount of fuel oil represented by the shaded area between the demand and supply curves. During this period, the economic price of the gas is clearly its fuel oil equivalent, and the total rent is the difference between that value and its cost of production, or $3/mBtu.

After T_1, the consumption of gas will depend on demand which, in turn, will depend on the price of gas. Assume for the first iteration that consumption followed the Q^{max} curve. This would represent the limiting case where gas consumption in each period would be as large as technically feasible, and therefore where the depletion date would be at its earliest. Then the economic price of gas could be calculated by noting that, at T^*_1, the depletion premium will again become $3/mBtu. This value could be deflated by the opportunity cost of capital to solve for the gas price for every period back to T_1. The price path for gas would then look like the curve shown in figure 3.

Such a price path would not represent the optimal one, however, because it is derived from first-round, rather than optimal, supply and demand schedules. On the supply side, it is based on the maximum supply scenario,

Figure 4
Initial trial solutions



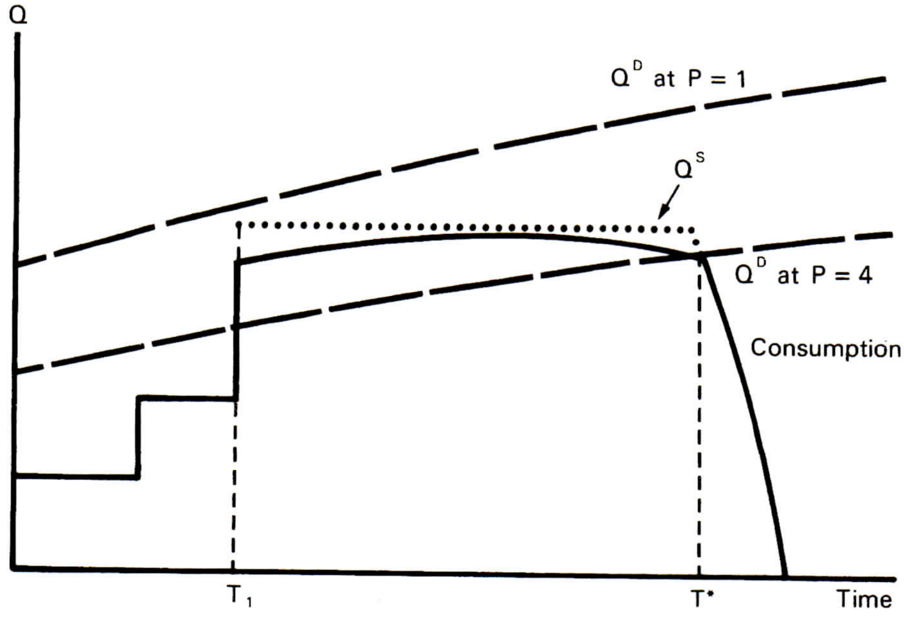
which produces excess capacity during much of the period between T_2 and T_1^*. It is inconsistent with the demand functions, because T_1^* is derived from a consumption path that would follow the supply curve (Q^{max}), whereas the full supply capacity at a point such as T_2 could only be absorbed at prices below \$1/mBtu. Thus, additional iterations are needed to find T* and V.

For the second iteration, assume that consumption is as low as is feasible by using the demand curve for P = 4. In that case, the capacity expansion that could be undertaken as early as T_2 would not be needed until some later date, T_3, when demand has grown enough to absorb the full production of the existing facilities. Taking into account this change, and the fact that consumption after T_1 will follow the demand rather than the supply curve, yields T_2^*, the new date at which consumption becomes constrained by reserves and therefore has a price equal to \$4/mBtu. T_2^* implies a new price path for gas which, during the period of potential excess supply, is everywhere below the one generated by the first iteration because the depletion premium is discounted from the more distant date T_2^*.

These first two iterations bound the range of feasible gas consumption, and thus T*. For the third iteration, select T_3^* midway between T_1^* and T_2^*. Derive a gas price path by calculating the depletion premium between T_1 and T_3^*. Using this price path — which will be low just after T_1 and gradually rising to reach 4 at T_3^* – derive the demand function and the schedule of supply investment needed to meet that demand. Further iterations on the price path should be undertaken in this manner until a consistent consumption path is obtained. **Figure 5** shows how it might look, where the heavy line represents the consumption path.

This graphical example illustrates the links described in the equations between the depletion premium, the economic price of gas, the quantity of gas demanded and the point of economic depletion, T*. The loop that they form represents the framework within which specific questions of gas utilization and supply investment can be analyzed. Once the general parameters of this framework have been determined for a particular country, the resulting estimate of the economic price path for gas can be directly used to develop a supply sequence (and cut-off point) or to calculate the NPV of any potential gas-using project. The next section outlines the practical steps involved in applying this general framework to issues of gas planning and project selection.

Figure 5
Final iterative solution



Application of the framework

The framework described above constitutes the first of three stages to a full gas planning model (GPM). It will provide a profile over time of the aggregate gas demand/supply balance. This sectoral context is necessary in order to derive one or more scenarios for the economic price of gas over the relevant time period. The second stage is to identify, evaluate and rank alternative packages of gas-using projects and related infrastructure investments. This project evaluation analysis will be based on the gas price scenarios derived from the aggregate sectoral work. Thirdly, consistency checking and sensitivity analysis should be undertaken to highlight any necessary revisions in the preceding two areas (and possible additional iterations) and to identify critical project design issues or information gaps that need to be filled before certain decisions on gas strategy should be taken.

Figure 6 illustrates these three parts of a GPM, the main components of each and the major relationships and connecting links among the components. The sectoral analysis (Part 1) begins with largely independent evaluations of aggregate gas demand (Box 1) as a function of the price of gas and aggregate supply (Box 2), perhaps based on several reserve assumptions. In Box 3, these are translated into time-dependent profiles of potential gas demand (at various prices) and supply (under various reserve scenarios). From this information and the costs associated with the investments for the aggregate supply scenarios, the long-run marginal cost of gas can be calculated (Box 4). Using the framework described above, the economic price path for gas is then derived in Box 5.

The actual project formulation and comparative project evaluation are carried out in Part 2. First potential projects are identified and grouped into tentative packages based on their technical characteristics and economic complementarities (Box 6). In the largest gas-using sectors, such as electric power and fertilizers, the aggregate demand analysis from Box 1 will have already identified a sequence of projects. To these will be added gas-using projects from other sectors and for the export market, and NPV calculations will be performed on the various trial packages (Box 7). If there is more than one gas price scenario, then there may be correspondingly numerous "optimal" project packages selected in Box 8.

In Part 3, the gas consumption stream implied by each optimal package is checked against the aggregate demand and supply analyses (Boxes 9 and 10). Any divergence should be traced through the steps in Part 1 to see if there is a significant impact on the gas price path. If so, another iteration through Part 2 will be needed. Once a consistent set of optimal project packages has been derived, a sensitivity analysis should be carried out (Box 11) in order to test the robustness of the results and to identify the critical areas of uncertainty in the analysis.[4]

Figure 6
Components of a gas planning model

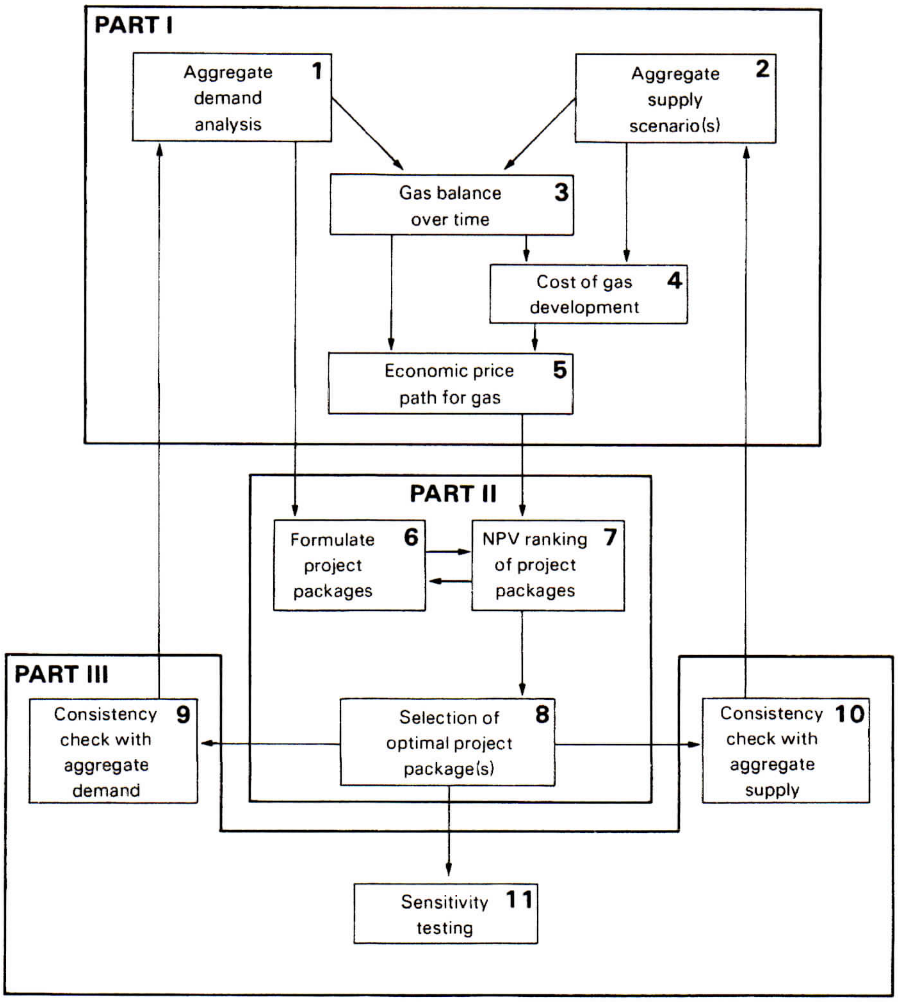


Illustration of the framework for country classification

While the analytical framework presented above is a general one that can be applied to all countries with gas, it is clear that certain aspects of the analysis will merit more attention in some cases than in others. The problems facing a gas-short country, such as Pakistan, will be different to those of a gas-surplus country, such as Bangladesh. This framework can be used to develop an issue-oriented classification of countries, which can help to highlight the particular concerns of each early in their gas development programmes. Using the general framework, this section defines three types of country (or region within countries) — gas-surplus, gas-short and surplus-window — and discusses the aspects of the general framework likely to be of greatest importance to each.

A gas-surplus country is one in which the demand/supply balance is such that T*, the point of economic depletion, is very far into the future. Once T* is 30 or 40 years away, the present value of the depletion premium in that year becomes insignificant, compared with the range of uncertainty surrounding other estimates, such as the cost of gas development. Thus, for practical purposes, the economic price path for gas over the planning horizon becomes the long-run marginal cost (LRMC) of gas development. This implies that relatively little time should be spent developing estimates of gas supply or aggregate gas demand (beyond what is necessary to establish that the situation is indeed one of gas surplus), and relatively more time should be devoted to defining the short- and medium-term investment programme in gas production and infrastructure, to provide a firm basis for the cost estimates. Once those are available, alternative gas-using options can be easily evaluated, using NPV calculations based on the LRMC of gas development. Questions of project sequence will not be paramount, since gas availability is not a constraint. The constraints to bringing projects onstream more rapidly will often be economy-wide ones: availability of capital, managerial skills, industrial infrastructure, etc. Therefore, careful attention should be paid to exploiting potential complementarities and economies of scale in gas investment.

A gas-short country is one in which the potential gas availability is projected never (or only briefly) to exceed the potential demand for it. In a number of countries, current fuel oil consumption is several times as large as natural gas production. Even if the latter increases significantly, with projections of continued economic growth, it is likely that incremental gas supplies will continue to replace fuel oil at the margin. In such a case, the economic price path for gas will follow that of fuel oil, so long as the cost of incremental gas supplies remains below that level. Since consumption will be supply-constrained in a gas-short country, more time should be spent on the demand side analysis than on supply. It will often be sufficient to develop alternative supply scenarios and to plot out Q^{max} for each (in a gas-short situation, T_1 will never be reached, so that $Q = Q^{max}$). The cost of gas development can be done roughly, simply to ensure that costs remain below the cost of the replacement fuel. Demand analysis should focus on identifying specific project candidates in the main domestic markets (e.g. electricity, fertilizer, cement), rather than estimating long-run trends in aggregate demand. Project packaging, ranking and selection will be the most critical part of the analysis for a gas-short country. With gas availability a constraint over the entire period, questions of project size and sequence are of major importance.

A surplus-window country is one for which the planning period includes times of both gas surplus and gas shortage. T_1 is either past or imminent, T^* is either projected within the planning period or clearly foreseeable beyond it, and the economic price path for gas will have a shape similar to that shown in figure 3. In such a case, there are few short-cuts to the full analysis that can be taken. Both demand and supply must be estimated carefully in order to derive T_1 and T^*, and thereby the gas price path. A general estimate of the cost of gas development will be needed to ensure that the price path does not fall below it. Issues of project timing will be critical, since some potential projects will become viable only after T_1 when the price of gas falls, and these should be compared initially on a mutually exclusive basis to find the best candidates for that possibly brief period of gas surplus. If more than one or two such projects are included in the planning period, a consistency check may show that the resulting level of aggregate gas demand in the years immediately following T_1 will raise the gas price path enough to crowd out the marginal projects. Because of the sensitivity of the gas price path to project selection in surplus-window cases, several complete iterations will often be required to arrive at a consistent plan for gas development.

Conclusion

The analytical framework presented in this paper can form the basis for the development of a gas planning model (GPM) that addresses the particular concerns facing a country with undeveloped gas resources. Once the basic framework has been set up, such a GPM is a simple and revealing tool for strategic planning in the gas sector.[5] Comparable with the power system planning models used routinely by decision-makers in the electricity sector, a regularly updated GPM can provide gas managers with a consistent framework to quickly test the effects of alternative investment decisions. In addition, it could be used for gas pricing analysis, tariff formulation or contract negotiations. As gas development proceeds, the GPM can also be expanded and made more sophisticated, by incorporating better information on reserves or better methods of demand forecasting.

Footnotes

1. *Additional detail on these and other aspects of gas planning can be found in the authors' forthcoming book, "Natural Gas: Economics and Policy in Developing Countries", a World Bank publication.*

2. *Strictly interpreted, this assumption would prevent the derivation of the Hotelling principle of depletable resource economics, since resource owners must be able to vary their production in response to price changes in order to derive the first order condition that the present value of profits in each period must be equal. The assumption is used here in order to permit a graphical presentation. The Hotelling principle is retained through the demand side so that the time trend of consumption follows the appropriate path, and it is introduced independently in the set of price equations.*

3. *For a comprehensive review of the Hotelling principle and its implications, see P.S. Dasgupta and G.M. Heal, "Economic Theory and Exhaustible Resources", James Nisbet and Co Ltd, Cambridge University Press, 1979. For a less technical treatment, see M.G. Webb and N.J. Ricketts, "The Economics of Energy", John Wiley and Sons, New York, 1980.*

4. *A detailed treatment of each of the GPM "boxes" can be found in DeAnne Julius, "Natural Gas Utilization Studies: Methodology and Application", World Bank Energy Department Paper no. 24, September 1985.*

5. *Trials of this framework in several developing countries have shown that it can be readily accommodated on a mini-computer operated by staff trained in using package software but without programming experience.*