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EUROPEAN GAS TRADE: A QUANTITATIVE APPROACH

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Preface

This second working paper within the series of reports on the ongoing activities in IIASA's International Gas Study presents some test applications of the GATE-I model (Gas Trade, Integrated Version). The general outline of this model can be found in the report, "Model of European Gas Production, Trade and Consumption" [3]. The GATE-I model has been applied to demonstrate the feasibility of modeling natural gas scenarios and the corresponding gas trade among the European subregions.

Altogether four scenarios were developed: a base case that provides an initial test of the prospects for natural gas in future energy strategies for the European continent and indicates the trade links needed to meet expected demand; a scenario in which different export price-to-quantity relations are assumed for the gas exporting regions of the Soviet Union and North Africa; a supply security scenario that incorporates some gas import dependency policy considerations; and a scenario in which environmental aspects are considered in terms of the costs of meeting SO_2 emission reduction requirements for enhanced natural gas consumption.

In sum, given the simplification needed to keep GATE-I relatively compact and computationally fast, the main objectives of the excercise have been fully met. The quantitative results of applying the model to the analysis of gas prospects for the above regions should not be considered conclusive, but are suggestive of possible trends with respect to gas use in these regions. The preliminary analysis is currently being followed up with more detailed investigations.

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INTRODUCTION

At the outset of the IIASA International Gas Study the Energy Systems Group recognized the necessity of deploying an adequate methodological framework [1]. Thus work on designing a set of models was initiated in January 1984, at the time the Study was formally begun. The goal is a set of models reflecting the regional aggregation of the European continent into major exporters and importers of natural gas; these models will account explicitly for the particular conditions of the energy system in each of the regions. The model set will include a trade model (GATE-L) that links the regional models.

Clearly the task of compiling the necessary data and information for developing and calibrating the regional models will require some months. Thus in the interim an integrated version of the model set (GATE-I) was developed and demonstrated at the European Gas Meeting held at IIASA from April 16-17, 1984. In developing this pilot model special attention was given to the problem of modeling natural gas trade among the subregions of Europe, given conflicting objectives between exporters, between exporters and importers, or between both.

The principal idea guiding the design of pilot model GATE-I was described in [2]. Briefly, GATE-I possesses the following features:

(a) It covers the entire energy chain, from resource extraction to end use conversion;

(b) It encompasses all of the subregions of the European continent (East and West) which eventually will be accounted for by the individual models;

(c) It accounts for the potential role of natural gas in interfuel substitution, given economics of gas usage and the competitiveness of gas at burner tip;

(d) It can determine regional indigenous natural gas supply, gas import desires, and export potentials; balance natural gas demand and supply; and define the corresponding market clearing gas price(s).

Hence, GATE-I comprises, in simplified form, all essential features of the planned set of regional models, including the trade algorithm of GATE-L. The degree of simplification and the necessary aggregation was governed by the absolute minimum requirements for analyzing interfuel substitution, i.e. competitiveness of natural gas in various energy markets, and interregional gas trade.

This report describes a first attempt in applying this general methodological framework and some preliminary quantitative results. It is important to stress that the primary purpose of this exercise was to demonstrate the feasibility of this modeling approach for accounting for the physical flows of energy from resource extraction to end-use conversion and natural gas trade flows. This involved limiting the present analysis to a single objective functional mode (cost-minimization). Thus the four scenarios presented in this report should be viewed only from the perspective of testing the methodology and related computer software. Neither the assumptions about future development of the model's exogenous parameters and variables nor the numerical results obtained should be considered conclusive.

The geographic aggregation used for the GATE-I model differs slightly from the configuration presented in the study outline [1]. Again, the regional aggregation serves the purposes of demonstrating the important features of the GATE-I model: practicability was awarded higher priority than perfect reflection of all regional energy systems modeled within GATE-I. For example, the regional energy systems of the gas exporting regions (Soviet Union, Norway and North Africa), are reflected only to the extent necessary for the analysis of gas export profiles. The off-shore gas fields commonly referred to as Norwegian gas are labeled North Sea, North Africa is used as an acronym for not only Algerian gas but all other potential African and Middle East gas exporters.

Table 1 shows the composition of the gas importing regions used in this exercise: East Europe consists of the CMEA (Council of Mutual Economic Assistance) countries, except the Soviet Union; North Europe comprises Norway, Sweden and Finland; South Europe includes all European countries at the Mediterranean Sea except France; and Central Europe comprises the nine member countries of the Commission of European Communities (CEC) except Italy plus the remaining Western European nations not otherwise accounted for.

Table 1. Aggregation of the European Countries into Regions.

Central Europe	Austria, Belgium, Denmark, Federal Republic of Germany, France, Ireland, Luxembourg, Netherland, Switzerland, United Kingdom
East Europe	Bulgaria, Czechoslovakia, Democratic Republic of Germany, Hungary, Poland, Romania
North Europe	Finland, Norway, Sweden
South Europe	Greece, Italy, Portugal, Spain, Yugoslavia

Regional Energy Systems in GATE-I

The representation of the regional energy systems emerged from an initially uniform structure for all regions which was modified to reflect the energy system characteristic of the individual regions. Figure 1 shows the initial structure of the regional energy systems: The primary energy resources considered are coal, oil, gas, nuclear power, and hydropower*, the fossil energy

*Nuclear energy and hydropower quantities are expressed in terms of thermal oil equivalent.

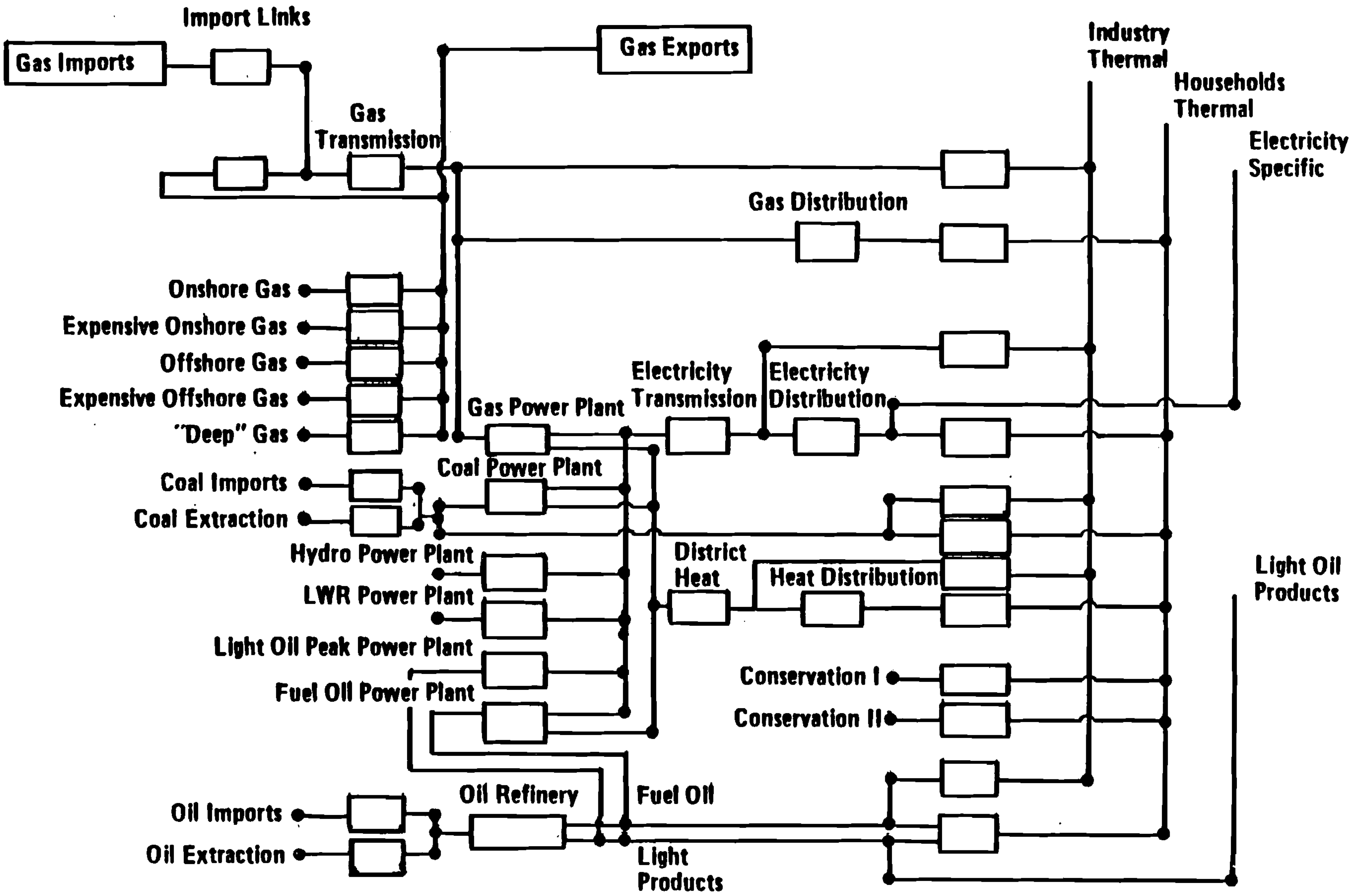

Figure 1. The Regional Energy System.

forms can be either domestically extracted or imported, or both. The next stage in this schematic representation of the energy chain concerns the conversion of fossil and nonfossil fuels into electricity or, when necessary, the up-grading of fuels, e.g. the refining of crude oil into such products as light oil (including gasoline, gasoil, LPG) and fuel oil.

The different forms of secondary energy, i.e. solids (primarily coal), light oil, fuel oil, gas, electricity and district heat (the latter used here only for North Europe) are delivered to consumers by means of transmission and distribution technologies. Finally, at the site of final energy consumption the delivered energy (in the form of final energy) is converted into useful energy.

All components of the regional energy systems are represented by a set of technological data such as conversion/transmission efficiencies, plant life, average operation-time per year, etc.

The useful energy demand sectors common to all gas importing regions are:

- Thermal energy needs in household and service sectors, primarily consisting of space and water heat;
- Thermal energy needs in industries, i.e. low- and high-temperature process heat, space heat, etc.;
- Specific uses of electricity, including all areas of electricity consumption where no substitution by other fuels is envisaged over the next decades; and
- Specific uses of liquid fuels, i.e. the fuel requirements of the transport sector and the nonenergy liquid fuel demand.

Natural gas exports originating from the USSR and North Africa are determined by means of export supply functions which simply relate export prices to the marginal quantities demanded. Within GATE-I, USSR gas export prices are given in terms of c.i.f. as of the CMEA/Western Europe border (e.g. the point of entry at the Austrian border). The transport costs of Siberian gas from the Urengoy fields to the Western European border are considered as part of the Soviet gas export prices, i.e. the export prices are subject to the USSR export and foreign currency earning policies and not necessarily to actual cost recovery considerations.

North African gas export prices are calculated in terms of the average f.o.b. at the outlet of the gas fields to the trunk line. Figure 2 gives the assumptions regarding the price-quantity relations underlying this analysis. Natural gas reserves/resources of either the USSR or North Africa were not reflected explicitly within the GATE-I applications for two reasons. First, the gas resources of both regions are considered plentiful over the time horizon of the study, and secondly, it seems reasonable to assume the willingness of both to export, provided that sufficient net backs can be materialized.

North Sea gas reserves and resources are, however, taken into consideration explicitly. In GATE-I these are four reserve/ resource categories, each of which is characterized by different technoeconomic parameters and extraction technologies. The average extraction costs of North Sea gas and the corresponding reserve/resource potentials are given in Table 2.

The largest natural gas producer among the net gas importing regions has thus far been the Netherlands. In addition to supplying some 50 percent of domestic primary energy needs with natural gas, the Netherlands have exported considerable amounts of gas to the countries of the Central European region as well as to Italy (South Europe). Given the size of Dutch natural gas

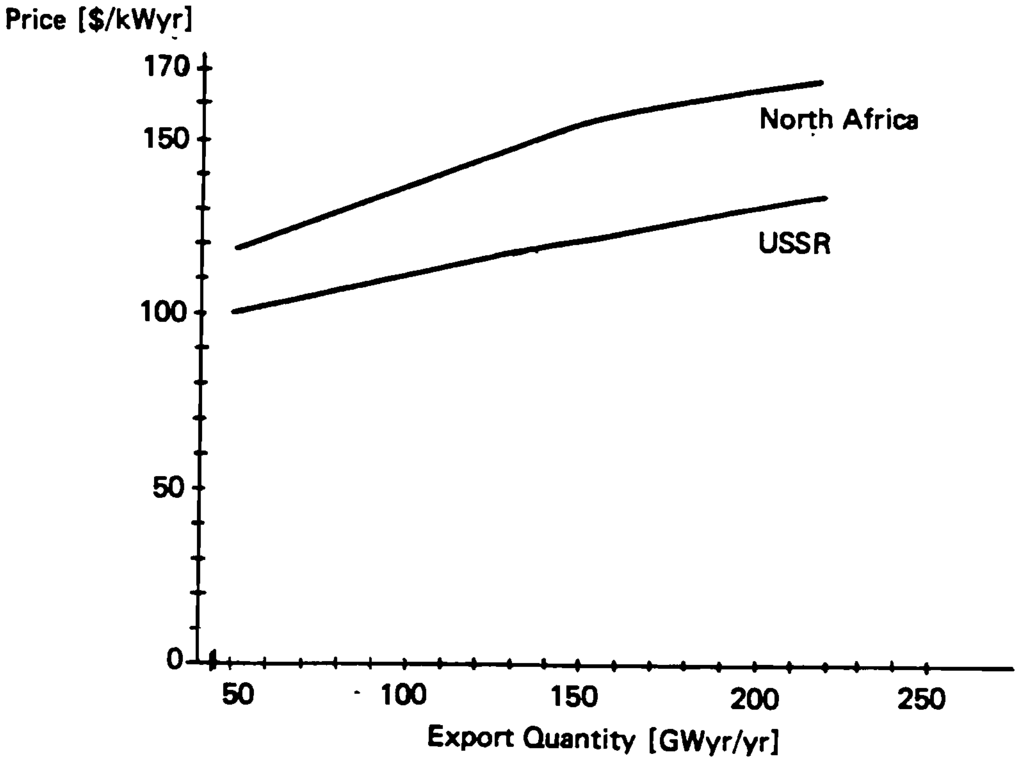

Figure 2. Relationships Between Gas Export Revenues and Willingness to Export for the USSR and North Africa in the GATE-I Pilot Version (Base Case).

Table 2. Gas Extraction Cost and Resource Potential per Region.

Region	Category	Cost $/kWyr	Cost $/10^6 BTU	Potential TWyr[a]
North Sea	Cheap 1	42.6	1.4	1.0
	Cheap 2	59.6	2.0	3.0
	Expensive 1	90.2	3.0	4.0
	Expensive 2	105.2	3.5	4.0
Central Europe	Onshore 1	26.4	0.9	1.0
	Onshore 2	45.4	1.5	3.5
	Offshore 1	60.0	2.0	1.5
	Offshore 2	100.0	3.3	5.0
	Deep	317.4	7.3	10.0
East Europe	Cheap	26.4	0.9	1.0
	Expensive	42.6	1.4	2.5
North Europe	Deep	317.4	10.6	5.0
South Europe	Cheap	31.5	1.1	0.3
	Expensive	65.5	2.2	1.0
	Deep	317.4	10.6	5.0

[a] 1 TWyr of natural gas is equivalent to 846.4 billion m^3.

reserves/resources, the current gas exporting policy of the Netherlands, and the fact that Dutch gas exports largely remain within Central Europe, Dutch gas has been treated as a domestic resource of the Central Europe region. Clearly, the gas production level for the Central European region had to be constrained so as to be consistent with Dutch policy on gas. The extraction costs and gas reserve/resources of the Netherlands, Central Europe, East Europe, North Europe, and South Europe are given in Table 2.

Gas Trade Flows

The interregional gas trade flow possibilities in the GATE-I model are based on the existing European trunk line grid as well as the planned extensions (see Figure 3). The level of use of the existing gas transmission infrastructure and new transport capacities are subject to the cost-optimizing objective function (with the exception of the USSR-Western Europe trunk lines). As already mentioned, the gas trunk lines (and the entire gas distribution infrastructure) are treated as individual technologies each with its own technoeconomic characteristics.

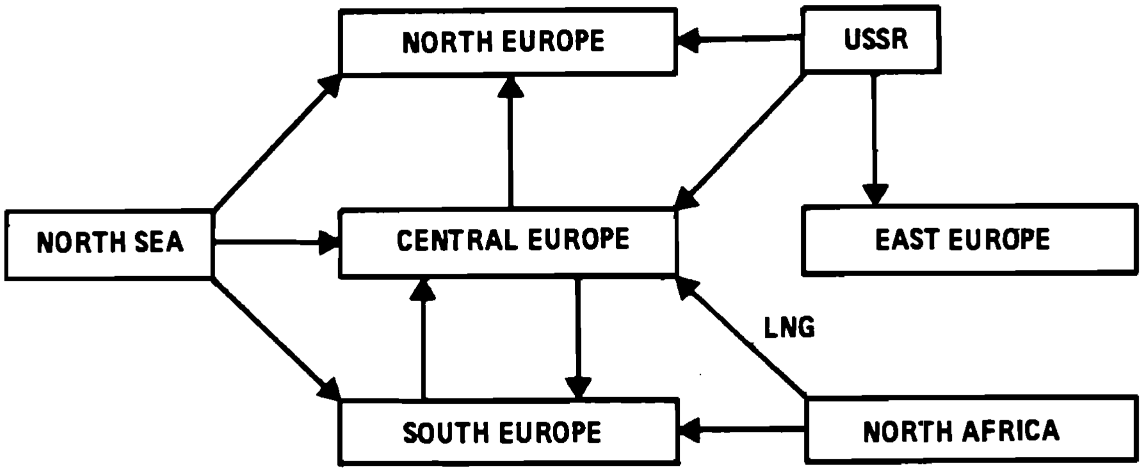

Figure 3. Possible Gas Flows.

Costs and Prices GATE-I

The technical data characterizing the various activities of extraction, primary-to-secondary conversion, transmission/distribution and end-use conversion are supplemented by a number of cost and price parameters. These parameters comprise unit investment costs, and fixed and variable operation and maintenance costs. Fuel costs are accounted for separately along the entire energy chain; they are simply the result of adding up all the technology costs that have been incurred up to the point of fuel consumption. At this point the distinction between costs and prices becomes a vital issue. All indigenous operations are quoted in terms of their costs, which as such are market prices. For example the investment costs and operation and maintenance costs associated with a specific technology can be considered as market prices in real terms. Or all energy imports are given in market prices. However, the corresponding output of this technology is quoted in terms of costs, i.e. without profits, taxes, etc. Thus, linking a number of technologies distorts the distinction between costs and prices. Furthermore, at the end-use level different prices are often associated with the same fuel depending on the scale of consumption. Therefore, a systematic approach had to be defined which compensates for this inconsistency between costs and prices.

In the GATE-I model historically observed rates for profits, taxes and other related costs were added to the output costs whenever necessary--i.e. before the energy flow enters another stage within the energy conversion chain or before it reaches the final consumer. At the end-use level, existing fuel price differentials between large consumers (industry) and households were retained.

Dynamics and Constraints in GATE-I

The dynamics of the GATE-I model over the 30-year study horizon are determined largely by the following factors:

Changes of the objective gradient which in this model means changes in costs or prices. Generally all costs and prices are quoted in real US dollars at 1980 prices and exchange rates. Essentially this implies constant costs and prices over the entire study horizon. There are, however, a number of exceptions where real price changes were introduced. For example, nongas import prices are assumed to rise (see Table 3). Further, the gas (fuel) extraction costs and in subsequent stages gas (fuel) prices increase in accordance with the rate of depletion of conventional and inexpensive resources.

Table 3. Price of Coal and Crude Oil Imports.

	Price in 1985		Growth (%/yr)	
Fuel	\$/kWyr	\$/10^6BTU	1985-2000	2000-2010
Crude Oil	242	8.1	2	1.5
Coal	200	6.7	2	1.5

Dynamic constraints. Maximum growth rates for the buildup of certain technologies. Dynamic capacity buildup constraints prevent sudden and total shifts from one technology to another. These constraints reflect the inherently long lead-times required to introduce major structural changes in complex systems, such as energy systems.

Resource constraints limiting the total use of a category of resources over the 30 year time horizon. Technical and economic considerations restrict the utilization of nuclear power plants to base load supply and disregard the generation of peak load electricity. Consequently, the contribution of nuclear power to electricity supply depends on the shape of the demand load curve. In the GATE-I model nuclear energy was confined to a maximum contribution of 35 percent of total electricity supply in the regions of Western Europe. Nuclear's share in electricity generation for East Europe was fixed at a maximum of 80 percent due to the relatively flat load curve and the CMEA policy of strongly enhancing the deployment of nuclear power.

Regional policy considerations. Security supply of considerations may impose ceilings on the supply dependency of a region or regions on any fuel (here natural gas) exporting region. For the current analysis the default maximum dependence of the Western European regions on a single gas exporting region is essentially unconstrained, i.e. the value adopted is 90 percent.

Future energy demand profile. The growth of useful energy demand is one of the major dynamic forces affecting the development of regional energy systems. The demand projections adopted in the present analysis (see Table 4) were derived from the low projections of the International Energy Agency [3].

Table 4. Energy Demand Projections per Region (GWyr/yr).

	1980	1990	2000	2010
North Europe				
HH TH	17.3	16.7	16.7	17.0
IND TH	19.2	21.0	23.0	24.9
SP ELEC	17.2	18.1	19.0	20.0
SP LIQU	26.6	26.6	26.9	27.4
Central Europe				
HH TH	201.3	200.3	214.8	230.3
IND TH	154.4	158.3	164.8	173.2
SP ELEC	83.9	92.7	106.5	123.6
SP LIQU	290.2	294.6	306.6	322.3
South Europe				
HH TH	42.4	47.4	52.9	58.7
IND TH	68.4	77.1	92.1	106.9
SP ELEC	29.1	33.1	38.4	44.6
SP LIQU	97.2	98.7	103.7	110.1
East Europe				
HH TH	88.3	100.0	134.4	198.9
IND TH	150.6	183.6	246.7	331.6
SP ELEC	31.6	35.6	41.3	48.0
SP LIQU	53.0	58.5	66.6	75.8

NOTE: HH TH is thermal use in the household sector; IND TH is thermal use in the industrial sectors; SP ELEC is specific electricity; and SP LIQU is specific liquids.

Scenarios and Model Applications

Prior to any modeling analysis of this kind it is necessary to calibrate the model to the base year or better the dynamics of the past. A careful model calibration enables one to reflect more accurately the energy flows along the entire energy chain, the existing stock of energy production capacities and their utilization, the age structure of the energy infrastructure, etc. In other words, the model should reflect the historical development of the energy systems as closely as possible. Clearly, there are limits to the goodness of fit between historical observations and model calculations. For example, the GATE-I model is a member of the MESSAGE II model family which in turn belongs to the class of dynamic linear/nonlinear programming models. These types of optimization models are difficult if not impossible to calibrate correctly because the real world rarely functions optimally. Also, a model can only be a simplified representation of reality. Consequently, the model's image of the energy systems will always differ from reality.

Given the available statistics, 1980 proved to be an appropriate base year for this analysis. The principal setup of the base year, the data used, etc. can be found in [2]. Primary and final energy consumption in the four European gas importing regions is summarized in Tables 5a and 5b.

Table 5a. Primary Energy Consumption, 1980 (GWyr/yr).

Europe	Solids	Crude Oil	Natural Gas	Nuclear[a]	Hydro[a]	Elec-tricity[a]	Total
North	21.0	64.7	2.4	11.4	40.9	0.2	140.6
Central	311.1	593.7	216.0	57.8	53.3	-0.6	1231.3
South	65.2	251.2	39.4	2.4	33.6	0.9	392.7
East	323.5	144.1	89.2	7.8	9.1	5.4	579.1
Total	720.8	1053.7	347.0	79.4	136.9	5.9	2343.7

[a]Given as primary energy equivalent.

Table 5b. Final Energy Consumption, 1980 (GWyr/yr).

Europe	Solids	Petroleum Products	Natural Gas	Electricity	Total
North	15.2	56.1	0.7	24.2	96.2
Central	93.3	498.3	179.5	118.1	889.2
South	32.3	178.1	35.1	39.8	285.3
East	216.8	124.1	69.8	41.9	452.6
Total	357.6	856.6	285.1	224.0	1723.3

Four scenarios were explored in this analysis. The first scenario--the Base Case--provides an initial test of the prospects for natural gas in future energy strategies for the European continent, and indicates the trade links necessary to meet expected demands. The Base Case represents a relatively unconstrained scenario where the potential of natural gas consumption has been determined entirely by economic considerations, i.e. burner competitiveness versus alternative fuels at the end-use side and net-back yields for the gas producers/exporters.

The second scenario assumed different export price-to-quantity relations for USSR and North African gas; the third scenario incorporated some gas import dependency policy considerations. The fourth scenario incorporates environmental aspects by means of confronting the costs of sulfur dioxide (SO_2) emission reductions with enhanced natural gas consumption.

Common to all scenarios is the regional economic outlook up to the year 2010. As mentioned above, the economic factors and to that extent assumptions about future useful energy demand are based on the low projections of the IEA analysis. Although the assumed aggregate economic outlook for Europe is modest, there are notable differences among the regional prospects. For example, there is the North-South disparity in economic well-being. The potential for traditional rates of economic growth appears to be larger for South Europe than for North Europe or Central Europe. Therefore the assumed energy demand growth rates of South Europe exceeds those of the other Western European regions. The growth assumptions for East Europe are based on personal communication with experts from the CMEA region.

Different regional energy demand growth rates have certain implications for the market penetration potential of natural gas. Generally, a low energy growth profile is not as favorable for the expansion of any specific form of energy supply as an accelerated growth situation. While in the latter situation the market penetration of, say, natural gas could be eased simply by absorbing the supply of the incremental demand, in a low growth environment any further market penetration means the displacement of other fuels.

Another set of exogenous parameters common to all scenarios is the non-gas energy import prices (see Table 3). Further, all dynamic capacity build-up constraints, etc. were kept unchanged throughout the scenarios.

The Base Case

North Europe. The energy demand outlook of North Europe is characterized by low growth rates of less than 0.5 percent per year for the period up to the turn of the century. All three countries of this region have successfully advanced the concepts of energy conservation along the entire energy chain during the 1990s. Furthermore, structural economic change has resulted in strong shifts away from energy intensive activities. The demographic outlook appears relatively stable and other socioeconomic indicators point to an almost constant demand for energy-consuming equipment, ranging from housing requirements to household devices. Hence, there is little margin left for drastic increases in energy consumption. Most of the effective energy savings measures will have been be implemented by the year 2000, so that few additional savings can be expected thereafter. This leads eventually to somewhat higher energy demand growth rates after the turn of the century than those observed for the years preceding this period.

On the supply side the nations of North Europe have adapted their domestic energy systems to their specific national resource situations. Apart from Norway, North Europe is poorly endowed with conventional fossil resources and both Sweden and Finland import some 50 percent of their primary energy consumption in the form of crude oil and oil products. During the 1970s both countries used their considerable peat resources and explored efficient uses of wood resources.

The only noteworthy energy resource available in all North European countries is hydropower. In 1980 Sweden and Norway generated 60 and 99 percent of their electricity needs from hydropower, respectively; hydroelectricity contributed 25 percent to electricity supply in Finland. Nuclear power plays an important role in the fossil resource poor countries of North Europe. Swedish and Finnish nuclear power stations produced 28 and 17 percent of total domestic electricity consumption respectively, which by international standards ranks them high among the nations producing electricity by nuclear power. The large contribution of hydroelectricity and nuclear power to domestic energy supply is also reflected in the high electricity share of some 25 percent in North Europe's final energy consumption (which is twice the share of these two sources in the final energy consumption of Central Europe).

Historically gas has played a negligible role in North Europe's energy supply menu. Because of lacking or undiscovered natural gas resources, the small quantity of gas produced originated as by-products (e.g. naphta in refineries, or coke oven and furnace gas) which was then utilized in town-gas systems.

Energy conservation and import diversification have been the main objectives of Sweden's and Finland's energy policies. Progress in the long-distance transport of gas and the development of Norway's off-shore gas fields created new prospects for the introduction of natural gas in Sweden and Finland. A number of feasibility projects have been launched to examine the gas import possibilities from both the USSR and Norway.

Investigations have indicated good prospects for natural gas in Scandinavia and have resulted already in definite contracts. Finland recently decided to import natural gas from the USSR, and the construction of a pipeline has begun. Sweden will soon import some Danish gas to the southern parts of the country. Other gas import alternatives are being investigated.

Norway's current energy policy does not consider the consumption of natural gas in domestic energy markets. Norway has the lowest population density of Europe, and these are only a few areas of sufficient energy demand densities to justify building a gas distribution infrastructure. Furthermore, the availability of domestic oil reserves currently overshadows the gas option.

The Base Case calculations indicate the continuation of the present trend regarding the development of North Europe's energy system (see Figure 4). Hydropower expands from 152 TWh(e)/yr in 1980 to 180 TWh(e)/yr in 2010, nuclear electricity production increases by 160 percent, whereas for both sources the major capacity additions take place after 1990. (We note that in this analysis the consequences of the 1980 Swedish referendum on nuclear energy have not been incorporated.)

The consumption of solid fuels (e.g. coal, peat, wood, shale oil) remains basically stable over the 30 year period, while oil consumption is reduced from its 1980 share of 49 percent to 31 percent by 2000 and to some 28 percent by 2010. The increases in nuclear and hydropower compensate for 50 percent reduction in oil use while the remaining 50 percent is covered by natural gas. By the year 2010 natural gas contributes 12.5 GWyr (or 7.7 percent) to North Europe's primary energy supply. In the light of the practically nonexisting gas infrastructure, the geographic pattern and absolute values of energy demand densities for natural gas appear reasonable.

The composition of final energy consumption indicated that natural gas faces strong competition in North Europe's energy market. Electricity expands its traditionally strong position in North Europe from 25 percent in 1980 to some 30 percent by the year 2010 (see Figure 5). Liquid fuels contribute 40

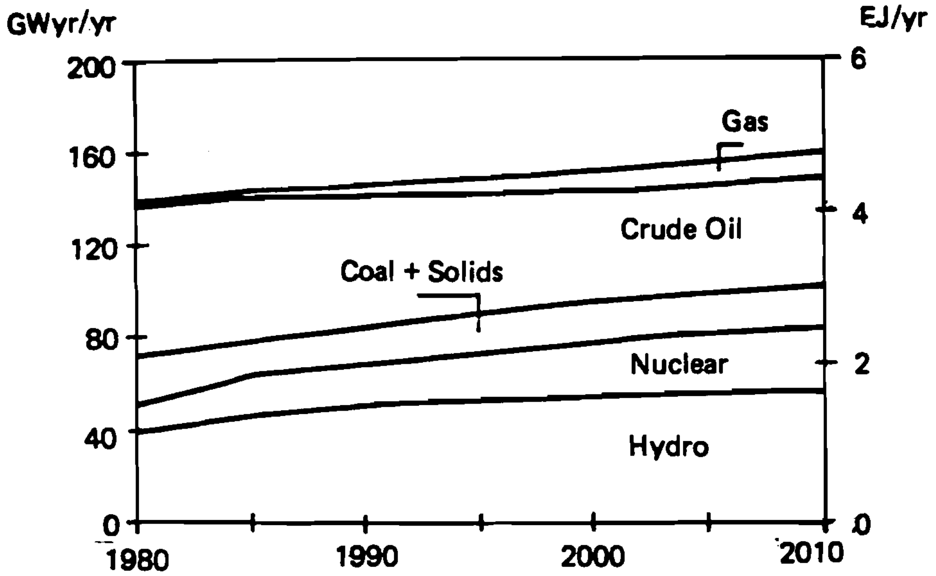

Figure 4. North Europe: Primary Energy Consumption or Equivalent, 1980-2010, Base Case.

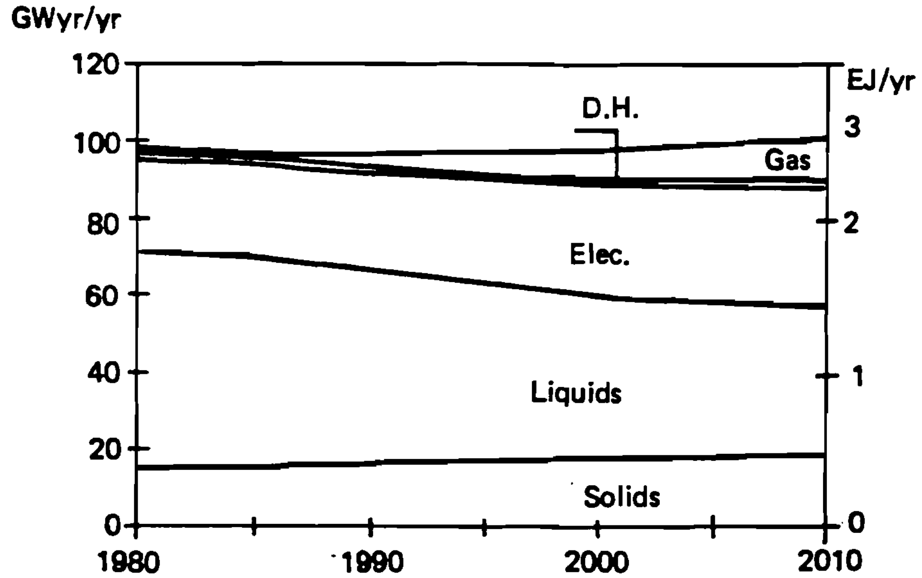

Figure 5. North Europe: Final Energy Consumption or Equivalent, 1980-2010, Base Case.

percent in 2010 (down from 55 percent in 1980), two-thirds of which are required to satisfy specific liquid needs. This is, over the period oil use for thermal needs is reduced by more than 50 percent compared to the base year liquid fuel consumption. Liquid fuel for thermal uses is consumed mainly in the household/service sectors, while in the industrial sectors gas and solid fuels almost totally substitute for liquids. Gas consumption is restricted to larger consumers such as industries that have sufficient energy demand densities to make gas economically attractive.

Central Europe. In 1980 Central Europe's primary energy consumption amounted to 1231 GWyr, which corresponds to more than two-thirds of the energy use in all of Western Europe. Central Europe includes the major economically active countries of Europe; thus the future economic and energy outlook of Western Europe will largely be shaped by economic developments, say, in the Federal Republic of Germany, France, or the United Kingdom. In terms of energy availability the region of Central Europe has few fossil resources, which are also often expensive to recover. Consequently, this region has become the largest energy (mostly crude oil) importing region worldwide. The UK is the only country with significant oil resources; but even these reserves supposedly are insufficient to maintain a production level above domestic needs in the long run.

Similar to North Europe, the national energy systems within the Central European region reflect the difference in national resource endowments. For example, the FRG and UK have the largest coal resources of Western Europe; although not necessarily based on cost considerations domestic coal supplies almost a third of these countries primary energy needs. Coal use in the remaining Central European countries amounted to some 17 percent in 1980 (or one-half the share of the traditional coal producing countries); of this amount more than 65 percent was imported. Altogether coal contributed 25 percent to this region's primary energy supply in 1980.

Natural gas resources are concentrated in the Netherlands and off-shore of the UK; minor gas resources can be found in the Netherland's neighboring countries. Not surprisingly, the Netherlands and the UK are among the largest gas consumers of Central Europe, i.e. almost 50 and 20 percent of their domestic primary energy consumption, respectively, in 1980. However, the situatin for natural gas is unlike that of coal where major producers turn out to be the major consumers. For example in 1980 natural gas held a 16 percent share in the energy supply menu of the FRG and France. The existence of a gas distribution and consumption infrastructure in the FRG and many other Central European countries (often in place since the last century when it accommodated coal-generated town-gas) has facilitated the market penetration of natural gas beyond the point determined by domestic resource availability. In particular, during the 1960s and the 1970s gas imports from the Netherlands enabled, for example, the FRG and France to base major parts of their energy systems on natural gas. The UK, the second major gas producer in Central Europe, absorbs all domestically produced gas and still has not yet reached selfsufficiency. Gas imports from the North Sea (Norway) and from Algeria (in form of liquefied natural gas--LNG) supplement natural gas supplies from UK's off-shore fields.

In summary, in 1980 the gas picture of Central Europe was dominated by the Netherlands which produced 99.4 GWyr or 46 percent of the gas consumed in the region. Of the total of 216 GWyr of natural gas consumed in Central Europe, 56.8 GWyr were imported: 32.3 GWyr from the North Sea, 22.2 GWyr from the USSR, and 2.3 GWyr from North Africa.

The potential for hydropower appears to be limited. The UK and the FRG, which together consume more than half of this region's primary energy, have almost reached the full potential of their relatively insignificant hydro resources. France and the countries located in the Alpine areas are somewhat better off, but in terms of the aggregate no large expansion is expected for Central Europe in relative terms over and above the current 4 percent of primary energy supply. The future of nuclear power must be viewed from the perspective of the different national policies. Generally, the prospects are good, although major contributions from this technology will depend on its economic competitiveness and sociopolitical factors.

The useful energy demand outlook for Central Europe resembles that for North Europe: Economic activity is assumed to recover slowly and the effects of both structural change and energy conservation result in the low energy demand projections shown in Table 4. Thus, natural gas must penetrate a stagnating market and compete with the well established energy carriers oil, solids (coal), and to a lesser extent electricity.

Before turning to the numerical calculations of the Base Case, it is necessary to recall some of the exogenous constraints imposed on the future development of Central Europe's energy system. For example, nuclear generated electricity has a ceiling of 35 percent of total electricity production. Hydropower, which is constrained by the region's lack of suitable rivers, becomes very expensive at the margin. Domestic coal extraction to a certain extent was forced into the model solution so as to reflect various national coal programs to support domestic coal use as opposed to using less expensive imported coal or other alternatives.

The final energy use in Central Europe (see Figure 6) is marked by the substitution of natural gas for liquid fuels (oil products). Natural gas expands its market share from some 20 percent in 1980 to 28.7 percent by 2010 at the expense of liquid fuels which drop from 56 percent to 43.6 percent over the study period. Hence, natural gas absorbs about three-quarters of the reductions in liquid fuel use. The remaining quarter is supplied by electricity (up to 16 percent from 13.3 in 1980) and some minor increases in solid fuels.

It is interesting to consider how the energy market is affected by this interfuel substitution. Unlike the situation in North Europe, in Central Europe gas penetrates the household and service sectors at a much higher rate than the industrial sectors. In the small users/household category gas consumption increases from one-third (in 1980) to two-thirds of useful thermal energy supply in 2010. Apparently, gas has reached an economically defined limit in this market. Gas covers all areas with sufficiently high energy demand densities where the gas distribution infrastructure costs are not yet so high as to prohibit gas' competitiveness. In reality, a share of maximum 60 percent might not be obtained. Gas substitutes not only for liquid fuels, but also for solids and electricity. This may suggest some overoptimistic assumptions within the Base Case scenario and the need to further analyze and modify the energy density areas underlying this pilot analysis.

Gas use for thermal purposes in industries grows at a slower rate than its direct competitors solids and electricity. This is a direct consequence of the domestic coal extraction assumed in this scenario. The lower limit of domestic coal production forces to open the question of how to use this coal. Coal combustion for electricity generation or for process heat supply in large industrial plants is the most economical approach. Both the indirect and direct

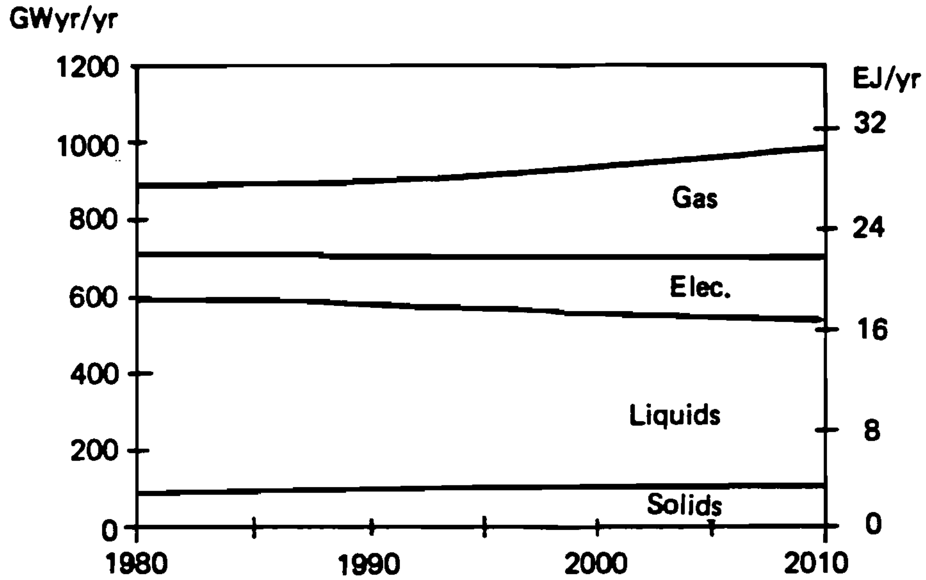

Figure 6. Central Europe: Final Energy Consumption or Equivalent, 1980-2010, Base Case.

effects of the coal policy in Central Europe restrict the expansion of natural gas in the industrial thermal market. But there is another reason for the limited market for gas. Specific liquid fuel uses amount to one-third of final energy demand comprising the gasoline and diesel needs of the transport sector, etc. An essentially unavoidable by-product of gasoline and diesel production is heavy fuel oil (the operational mode of the Central European refineries are assumed to produce a minimum of 10 percent fuel oil output). Similar to coal, the fuel oil market consists of electric utilities and industries. Hence, fuel oil maintains a market share of almost 19 percent within the industrial thermal market.

In summary, in Central Europe gas continues to dominate the industrial thermal market but faces competition from both coal and electricity. By the end of the study horizon gas supplies 39 percent (up from 36), fuel oil 19 percent (down from 28), solids (coal) 30 percent (up from 26), and electricity 13 percent (up from 10).

The electricity sector of Central Europe (see Figure 7) is characterized by a strong market penetration of nuclear power, which increases its market share from 15 percent in 1980 to the maximum contribution permitted in this scenario of 32 percent or 519 TWh(e), which corresponds to an annual installation of approximately 2 GW(e) over the next 30 years. Hydroelectricity decreases in relative terms from 13.7 to 12.6 percent but in absolute kWh produced hydropower expands by some 20 percent to 193 TWh(e)/yr by 2010.

Electricity generation based on coal remains almost stable throughout the study period. The 600 TWh(e) produced towards the end of the period reflect a market share of 39 percent (1980: 47 percent) and a slight increase of coal combustion of 9 percent. Light oil as a fuel for electricity generation is discontinued by 1990, with the phaseout of fuel oil completed by 2010.

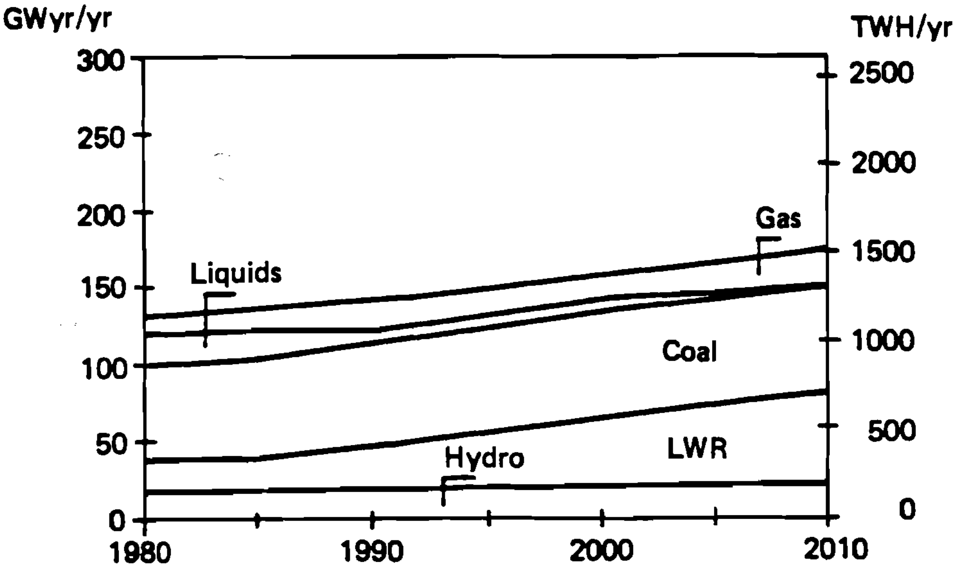

Figure 7. Central Europe: Electricity Generation, 1980-2010, Base Case.

The role of gas in the electricity market appears to be that of a swing supplier. Since most of the other options are constrained, gas not only displaces oil products in peak load supply, but also steps in whenever there occurs a gap that must be filled. Hence, the gas input to electricity supply varies over the period from 10.4 and 14.6 percent.

The primary energy consumption of Central Europe grows by 0.3 percent annually and reaches 1352 GWyr by 2010. Figure 8 illustrates the dynamics of the substitution of natural gas and nuclear power for crude oil and to a lesser extent for coal. Crude oil consumption decreases from 48 to 34 percent while a substantial part of this decline is offset by the increase of gas from 18 to some 27 percent. Nuclear power expands by seven percentage points and contributes 11.8 percent to primary energy supply in 2010.

In summary the Central European region offers good prospects for the market penetration of gas. However, the numerical results--in no way definitive--indicate that natural gas as a stationary fuel may be confined by an upper ceiling. Although the present calculations are based on assumptions that favor the expansion of gas, only 27 percent (as compared to the share historically held by crude oil) of the primary energy market are supplied by gas. Gas successfully penetrated the thermal market but given a 35 percent demand for specific (nonsubstitutable) liquid fuels any additional expansion will call for gas to be offered to final consumers in liquid form.

South Europe. In general the economies of South European countries are less developed than the other Western European economies. In terms of Gross Domestic Product per capita (GDP/cap) the value of Central Europe is more than twice that of South Europe. In 1980 the energy intensity in South Europe or energy input per dollar GDP produced was slightly above the energy intensity of Central Europe. Hence, any narrowing of the gap in the economic well-being

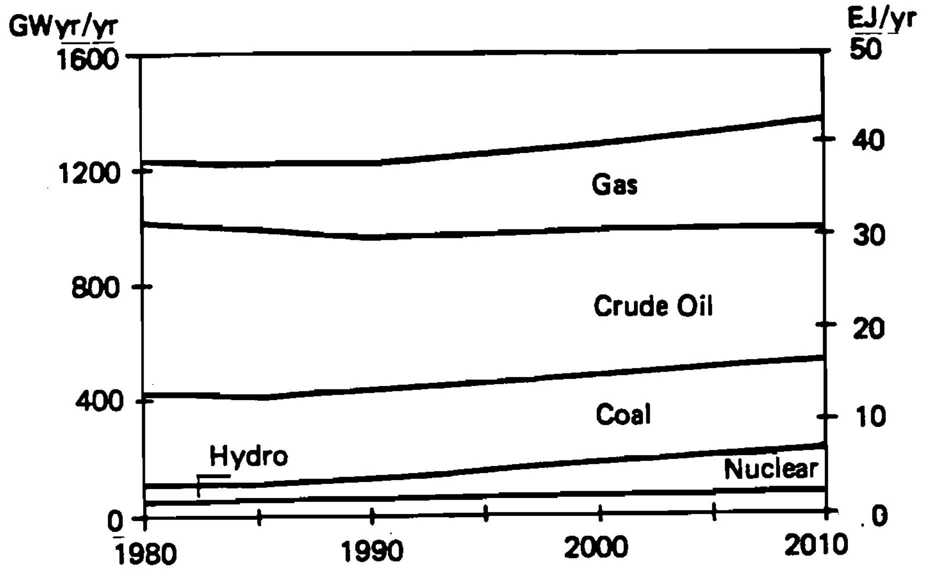

Figure 8. Central Europe: Primary Energy Consumption or Equivalent, 1980-2010, Base Case.

between South Europe and the remaining regions of Western Europe implies energy consumption growth rates in South Europe considerably higher than those in the other Western European regions. The useful energy demand development derived from the low projections of the IEA [3] reflect the aspirations of South Europe's economies to improve their relative economic position within Europe. As will be seen later this translates into the highest primary energy growth ra es of all regions of Western Europe.

The resource situation of South Europe is the poorest in Western Europe. With the exception of Italy, oil and gas resources are practically nonexisting, while the situation for coal is only somewhat better. Spain and Yugoslavia have some coal reserves but they are barely sufficient to satisfy their domestic needs. Nuclear power has recently reached the threshold of becoming an important energy source for the future, since the potential of hydropower has not been fully exploited so far some additional 15 to 20 GW could come online in the future.

The 1980 primary energy consumption profile of South Europe is dominated by the highest oil dependence of Western Europe, i.e. 64 percent of primary energy consumption; coal use accounted for 16 percent, and gas consumption for 10 percent. Given the poor resource availability of South Europe, the energy import dependence is significant: Oil more than 95 percent, coal 41 percent, and natural gas 54 percent.

Italy is the only country of South Europe that has a large-scale gas infrastructure in place. In 1980 16 percent of the domestic primary energy consumption was supplied by gas, of which more than 50 percent was imported. However, gas distribution systems, partly originating from the town-gas era, are being expanded or newly constructed in most of the nations of South Europe.

There are a number of ex-ante reasons which justify the expectations for natural gas as a major fuel in South Europe's future energy supply. First, this regional energy system has not yet reached the level of complexity, say, of North Europe. Second, the high energy demand growth rates assumed reduce the necessity for competition, so that gas could succeed in meeting the additional demand. Third, although the oil import dependence of this region cannot be reduced by natural gas, the expanded use of gas would comply with the regional policy of import diversification.

The Base Case calculations result in the expected substitution of gas for oil in final energy markets. However the sectoral allocations of the substitution processes are somewhat surprising. In the household and service sectors, gas looses its market shares both in absolute and relative terms, while that of light oil expands drastically. Electricity and solid fuels maintain their absolute contributions but decline in their relative importance.

In the industrial sectors a totally opposite development picture emerges. Gas increases its market share from 23 to 70 percent during the study period, displacing all its competitors, in particular fuel oil (which decreases its share in final energy from 45 to 14.7 percent).

The explanations for this outcome are straightforward. The energy demand densities in South Europe are much lower than in Central Europe. Additionally, the climatological conditions require less space heating, decreasing demand densities even further. Since GATE-I operates with a single average demand density, it does not distinguish between rural and urban areas; the average applied in these calculations is too low to be able to distinguish between gas use in household and service sectors. Industrial consumers usually consume larger-scale quantities and also require a less complex distribution infrastructure. Hence, natural gas is the preferred fuel in these sectors.

The primary energy consumption of South Europe is depicted in Figure 9. Natural gas and nuclear power expand their market shares drastically at the expense of crude oil and coal. By the end of the study horizon gas holds a share of 31 percent, crude oil of 42 percent, nuclear and hydropower 10 percent each, and coal 7 percent. Given the reduction of gas use in the household and service sectors, the large contribution of natural gas to primary energy supply must be the result of gas' penetration into the electricity generation sector.

The electricity sector is marked by the phase out of all coal- and oil-fired power stations by the end of this century. Initially the fast introduction of nuclear power plants and the additions of hydropower capacities substitute for fossil fuels. As of 1990 gas-fired power plants are installed at an increasing rate. By the year 2010 natural gas fuels more than one-third of all electricity produced.

The Base Case results for South Europe show the expected major increase in gas consumption. However, the dynamics of the substitution processes of gas for other fuels, as well as a careful distinction of energy demand density areas, e.g into urban and rural areas, must be further analyzed.

East Europe. The dominant component of the East European energy system is coal which in 1980 supplied 56 percent of this region's primary energy consumption of 579 GWyr. All countries in the region have sufficient coal and lignite resources but often of such low quality that extraction is difficult in terms of both economics and the environment. Poland, the German Democratic Republic, and Czechoslovakia posses the region's largest coal resources and are the largest coal producers. Poland's production exceeds their domestic

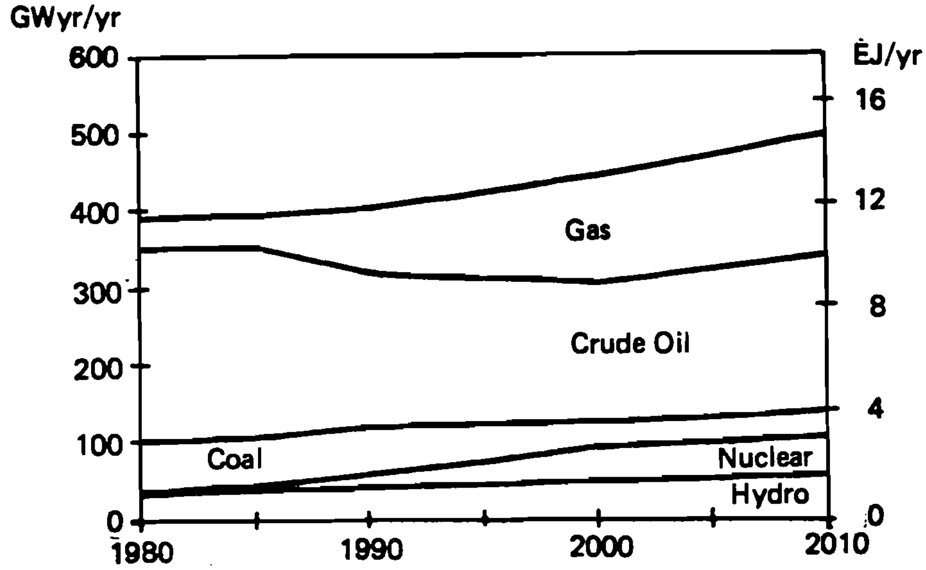

Figure 9. South Europe: Primary Energy Consumption or Equivalent, 1980-2010, Base Case.

needs and some 14 percent of their 1980 production were exported. In general, as coal is the only significant energy resource of the region, most countries' energy plans call for increased production in the future.

The resource situation with respect to oil and natural gas does not appear to be as bright. Apart from Rumania there are only insignificant oil resources available and the Rumanian reserve-to-production ratio has been declining recently at rates that suggest that their oil fields will be depleted before the end of this century. In 1980 Rumania's oil production did not suffice in meeting domestic oil needs, and like all the other East European countries Rumania had to import oil. The natural gas resource picture is similar to that of oil. Rumania, and to a lesser extent Hungary and Poland, have some gas resources, but the domestic production levels fall short of meeting domestic consumption needs. Consequently all East European countries are large importers of crude oil and natural gas. Most of these imports are supplied by the USSR but in cases where allocated import quotas were surpassed oil had to be imported from the Middle East against hard currency payments. In 1980 crude oil and natural gas contributed 25 and 15 percent, repectively, to primary energy supply.

The Base Case scenario specification concerning the useful energy demand projections (see Table 4), the dynamic capacity constraints and the general energy policy for East Europe are the result of private communication with experts from the CMEA countries. The energy policy assumptions of this analysis reflect the objective of maximizing self-sufficiency. This corresponds to minimizing oil and natural gas imports and expanding national coal and nuclear programs to their limits.

The high (compared to the Western European regions) final energy demand growth rate of 2.4 percent per year in this analysis puts enormous pressure on the East European energy supply system. Even with optimistic assumptions regarding the capacity expansion of domestic coal extraction in this region the high share of coal in primary energy supply cannot be sustained (coal output rises by some 70 percent from 323 GWyr to 550 GWyr over the study horizon), and coal's contribution to primary energy supply declines to 52 percent (see Figure 10).

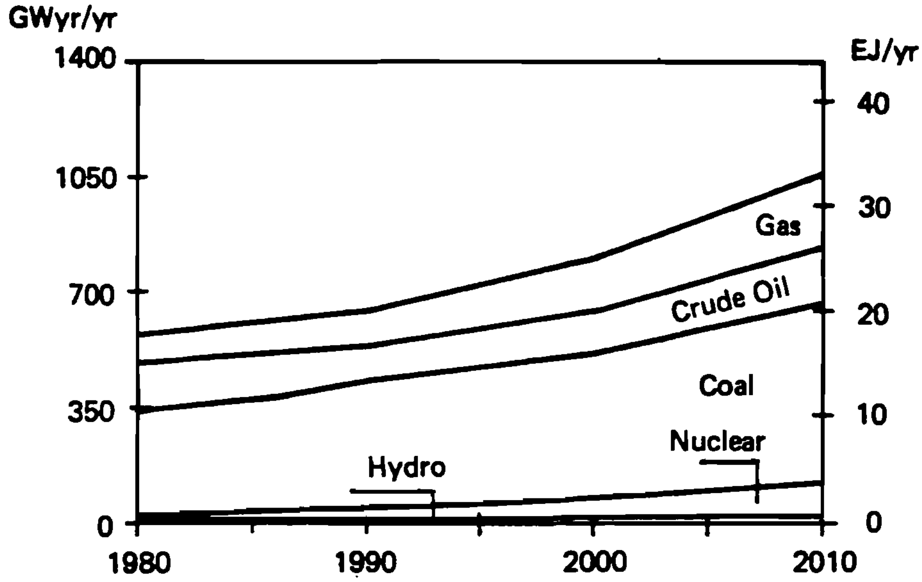

Figure 10. East Europe: Primary Energy Consumption or Equivalent, 1980-2010, Base Case.

Crude oil consumption declines until 1990 in absolute and relative terms but thereafter grows again at a slightly lower rate than total primary energy consumption. By 2010 some 220 GWyr of crude oil are being consumed (1980: 144 GWyr). The reason for this rebound of oil use is the rapidly growing demand for specific liquid fuels. While during the eighties conservation efforts and interfuel substitution permit a reduction in oil consumption this cannot be continued any longer after 1990 given the assumed final energy growth profile.

Natural gas replaces liquid fuels in the industrial sectors and to a lesser extent in the household and service sectors' thermal energy supply, while nuclear power and hydropower substitute for coal, oil, and gas in electricity generation. By 2010 some 50 GW(e) of nuclear power will have to be installed in East Europe to meet electricity demand. Gas increases its market share from 15 percent to 21 percent by 2010, nuclear from 1.3 to 9.5 percent, while hydropower maintains its 1980 share of approximately 1.5 percent.

A brief look at the development of final energy supply (see Figure 11) shows the increasing contribution of all energy carriers. In relative terms this is only true for solids and natural gas; for liquid fuels and, surprisingly despite the considerable expansion of nuclear power, for electricity there are declines. These trends, however, are different in the household/service sectors and the industrial sectors. In the former sector solids (coal) and light oil increase in absolute and relative terms, natural gas increases slightly in absolute use (but declines in share), and electricity decreases in absolute terms. In the

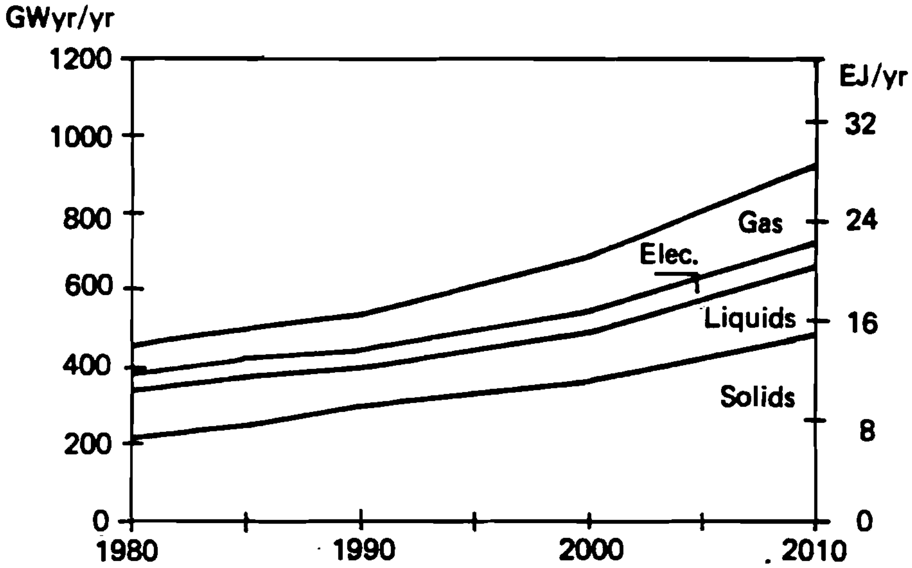

Figure 11. East Europe: Final Energy Consumption or Equivalent, 1980-2010, Base Case.

industrial sectors gas doubles its market share to 40 percent displacing liquid fuels, solids, and electricity at varying rates. While solids and electricity are still growing in absolute terms, liquid fuels use declines significantly during the initial periods and grows again towards the end of the study period. Again this development is a consequence of the specific liquid fuel demand and the operation modes of the refineries. There is simply too much residual fuel oil available which is best used for fueling large industrial boilers.

In summary, these preliminary results provide some insights into the development of the East European energy system. However, more analysis is needed. Specially, more detailed information is needed on end-use conversion, such as energy demand densities, conversion efficiencies, equipment's age structure, etc.

NATURAL GAS PRODUCTION AND TRADE

In 1980 natural gas contributed about 15 percent or 258 GWyr to Western European primary energy consumption. Interregional gas trade (excluding trade within the CMEA block) accounted for 79.2 GWyr or roughly one-third of total gas consumption. In terms of gas import dependence, some 5 percent of total primary energy consumption in Western Europe originated from nonindigenous regional gas fields. The breakdown of the gas import dependence of Western Europe (in relation to natural gas consumption) according to the principal exporting regions is as follows: USSR 13.1 percent, North Africa 2.4 percent, North Sea 12.5 percent, and 2.7 percent interregional trade among the Western European regions. East Europe imported 37 percent of its domestic gas needs exclusively from the USSR.

In the Base Case scenario the market for natural gas doubles by the year 2010, reaching some 27 percent of primary energy consumption or 534 GWyr. During the study period the gas import dependence of Western Europe increases from 30 to 66 percent. In terms of primary energy consumption this implies a dependence of 18 percent. The origins of the gas imports are shown in Table 6.

Table 6. Natural Gas Imports per Origin in GWyr and in Percent of Primary Energy Consumption of Western Europe.

Region	1980	1990	2000	2010
USSR	33.8 (1.9)	105.6 (6.0)	144.0 (7.7)	192.1 (9.6)
North Sea	32.2 (1.8)	38.5 (2.2)	64.1 (3.4)	77.8 (3.9)
North Africa	6.1 (0.4)	31.3 (1.8)	62.9 (3.4)	88.2 (4.4)

The sources of regional gas supply vary between regions and depend on domestic resource availability and their extraction costs as well as on the geographic location relative to the exporting regions. According to Table 7 North Europe imports 100 percent of its gas needs from the USSR, the North Sea and Central Europe (Denmark). In the light of the gas import price patterns assumed in the Base Case the option of drilling for deep gas does not seem to be economic.

Table 7. Sources of Gas, North Europe (GWyr/yr), Base Case.

	1980	1990	2000	2010
North Sea	-	-	4.4	7.8
Soviet Union	1.2	2.9	2.9	2.8
Central Europe	-	-	0.5	0.9
Total	1.2	2.9	7.8	11.5

Apart from a steadily increasing gas import dependence, natural gas supply of Central Europe is characterized by a decline of domestic extraction activities until the turn of the century; thereafter a rebound of indigenous production occurs which puts production back to the 1980 level. As will be explained later, this development is the direct result of the gas exporters' price-quantity relations (i.e. the elasticity functions which reflect the willingness to export at a certain price) underlying the Base Case scenario. The gas extraction profile of Central Europe shows a gradual transition from current low production cost resource categories towards higher cost categories. For example, by the year 2010 the traditional on-shore resources (on-shore 1 in Table 8) have been totally depleted and replaced by more costly on-shore and off-shore resource categories.

The gas imports grow steadily (almost by a factor of four) over the entire study period. The origins of these imports vary over the study period (see Table 8). Up to the year 2000 all three principal exporting regions expand their gas deliveries to Central Europe. During this period the Soviet Union replaces the North Sea as the largest gas supplier to Central Europe. The Soviet gas market share could have been even larger if the export capacity, i.e. the trunk lines

Table 8. Sources of Gas, Central Europe (GWyr/yr), Base Case.

	1980	1990	2000	2010
Domestic				
Onshore 1	85.0	47.2	12.8	-
Onshore 2	35.0	53.5	79.2	96.6
Offshore 1	46.2	46.4	27.8	16.6
Offshore 2		6.1	15.8	41.1
Total	166.2	153.3	135.6	154.3
Imports				
North Sea	32.3	38.5	59.7	69.9
Soviet Union	22.2	58.6	96.7	146.4
North Africa	2.3	20.0		
Total	56.8	117.1	156.4	216.3

from Urengoy to Central Europe, would have a larger capacity. The export strategy of the USSR is approximated by shaping the supply elasticity function so that Soviet gas prices underbid any non-European competitor by 10 percent. The export sales potential, however, is limited by the existing and planned long-distance trunk line capacities linking Siberia with Western Europe. This opens the opportunity for North African gas to participate successfully in the gas export sales competition in Central Europe. During the 1990s North African gas contributes some 17 percent, the North Sea 33 percent, and the USSR 50 percent to the gas imports to Central Europe. After the turn of the century the Soviet Union enlarge their gas export capacities at a rate that would permit their price advantage to push North African gas out of the Central European market.

By the end of the study period the Soviet Union exports 146 GWyr of natural gas to Central Europe which corresponds to a share of 68 percent of this region's gas exports. This export volume requires the field errection of three to four trunk lines similar to the one currently being put into operation for the transport of Siberian gas to Western Europe.

The North Sea supplies the remaining 32 percent or 70 GWyr of Central Europe's gas import needs. This export volume is the result of pure economic considerations at the aggregate level of Europe and thus does not reflect current or future Norwegian gas export strategies. Table 9 contains the natural gas extraction profile of the North Sea which once more depicts the inevitable transition toward costlier gas resource categories.

Table 9. Extraction Profile for North Sea Gas (GWyr/yr), Base Case.

	1980	1990	2000	2010
Cheap 1	33.5	29.8	27.0	22.06
Cheap 2	-	9.5	20.4	30.3
Expensive 1	-	-	18.0	27.0
Expensive 2	-	-	-	-
Total	33.5	39.3	65.4	79.2

Although South Europe's domestic gas production increases slightly from 18 to 25 GWyr--by shifting to the higher extraction cost resource category--the domestic gas supply remains insignificant compared to the import requirements (see Table 10). Gas imports from the USSR grow fourfold between 1980 and 1990 to some 40 GWyr/yr and remain constant until 2010. North African gas flows set in slowly and replace former imports from Central Europe (i.e. the Netherlands). Between 1990 and 2000, however, North African gas export explodes from 10 GWyr to 61 GWyr. Thereafter North African gas sales to South Europe continue to grow but at a more modest rate and reach 86 GWyr/yr by the year 2010.

Table 10. Sources of Gas, South Europe (GWyr/yr), Base Case.

	1980	1990	2000	2010
Domestic				
Cheap	18.2	13.9	7.1	-
Expensive	-	10.0	25.0	25.0
Total	18.2	23.9	32.1	25.0
Imports				
Soviet Union	10.4	42.6	42.6	40.5
Central Europe	7.0	7.0	-	-
Northern Africa	3.8	10.0	61.7	86.4
Total	21.2	59.6	104.3	126.9

At this point it is helpful to look at the export functions of the USSR and North Africa in some greater detail. One principal statement made above concerned the USSR export price strategy of underbidding non-European competitors by 10 percent. Clearly, a strict application of this strategy within a cost minimization approach would result in a total dependence on Soviet gas of all gas importing regions, and North African gas would be pushed out of the market. In order to avoid this unrealistic situation the following pricing method was introduced: The export price elasticity functions were disaggregated into discrete categories of fixed quantities and prices (elasticity categories) by means of step functions. The Soviet gas sales price is 10 percent lower per comparable elasticity category. This implies that Soviet gas has an initial cost advantage compared to other gas exporters. When the allocated quantity per lowest category is depleted and the next (more expensive) category becomes effective it may well be that the lowest categories of the approximated North African export function break even and are competitive. This procedure and the aggregate cost minimization objective function deployed in this study lead to the South European gas import pattern depicted in Table 10. Soviet and North African gas exports are assumed to follow the price-quantity relations as shown previously in Figure 2. In the Base Case the North African gas exports lag behind the USSR sales by approximately one elasticity category per time interval (see Tables 11a and 11b). In other words, the cost minimizing objective raises the export sales up to the full limit of an exporter's elasticity category before the next one or the competitor's category are allocated. The fifth elasticity category of the USSR turns out to be costlier than the expensive-to-extract domestic gas resources of Central Europe. Consequently gas imports do not expand beyond the fourth category and domestic gas production increases again.

Table 11a. Gas Export Profile for the Soviet Union (GWyr/yr), Base Case.

Elasticity Class	Price[a] 10^6BTU	1980	1990	2000	2010
1	3.3	34	50.0	50	50
2	4.0	-	50.0	50	50
3	4.7	-	10.0	50	50
4	5.4	-	-	-	50
5	6.0	-	-	-	-

[a]For these prices the same growth rates as for oil and coal imports are assumed (see Table 3).

Table 11b. Gas Export Profile for Northern Africa (GWyr/yr), Base Case.

Electricity Class	Price[a] $/10^6$BTU	1980	1990	2000	2010
1	3.7	6.0	30	30	30
2	4.4	-	3	30	30
3	5.2	-	-	4	30
4	5.9	-	-	-	-
5	6.6	-	-	-	-

[a]For these prices the same growth rates as for oil and coal imports are assumed (see Table 3).

North African gas exports to Central Europe fill a temporary bottleneck when the Soviet pipeline capacity build-up constraints hold back additional exports. After this capacity bottleneck has been overcome, North African gas prices at burner tip become unattractive due to the gas transport costs to Central Europe. The shorter distance to South Europe offsets this disadvantage and North African gas sales exceed USSR exports.

The gas trade pattern which emerged from the Base Case showed some interesting features regarding the origins of natural gas imports of the Western European regions. By and large the critical parameters determining the gas trade flows are the elasticity categories of the USSR and North Africa and, to a lesser extent, the gas transport infrastructure costs. The next paragraphs will attempt to cast some light on the question of the sensitivity of gas trade to varied export elasticity functions.

ALTERNATIVE GAS EXPORT ELASTICITY FUNCTIONS

The sensitivity analysis of the gas trade pattern to changes in gas export prices is based on two different sets of export price elasticities. Common to both sets is the elimination of the 10 percent price differential between Soviet and North African gas export prices per comparable elasticity category. The first set labeled Low Price (LP) assumes the adjustment of the North African prices to the level of USSR export prices. The second test, labeled High Prices (HP), assumes the reverse adjustment, i.e. Soviet prices are raised to the North

African level previously applied in the Base Case. All other exogenous assumptions are identical with the Base Case scenario.

The likely effects of the Low Price scenario which improves the competitiveness of North African gas exports in Western European energy markets may be

- Gas import diversification or simply a step towards a buyer's market;
- An expansion of the regional gas markets, i.e a higher rate of interfuel substitution;
- A combination of the two.

The LP scenario is a representative case of the combined effect.

Gas Import Diversification. North African gas exports to South Europe increase by more than 30 percent (compared to the Base Case) and reach 114 GWyr/yr by 2010. The total gas imports of South Europe, however, remains constant, while domestic gas production equals the Base Case development. Consequently the imports from the USSR were reduced by exactly the increase in North Africa's exports. Actually, without the constraint of a maximum 90 percent gas import dependence on a single exporter, the switch to North African gas would have been 100 percent. Given the price parity of USSR and North African gas at the respective entry points to Western Europe, as modeled in GATE-I, i.e. the Western European border for the USSR gas and the gas fields (net backs) for North African gas, this switch from USSR to North African gas implies that in the Base Case the Soviet exports to Western Europe are physically or economically limited, e.g. due to dynamic build-up constraints regarding the gas transport infrastructure or the shape of the export price elasticity function. Otherwise the Base Case exports of the Soviet Union should have been higher by the equivalent amount of the increase in North African gas exports in the LP scenario.

Market Expansion. The changes in the gas import structure of South Europe cause notable changes in the energy system of Central Europe, while North Europe is not affected at all. The additional gas export quantities available at an approximately 10 percent discount per elasticity category are immediately absorbed by the Central European market expanding the share of natural gas from 27 percent (Base Case) to 30 percent (LP). This points to a relatively price-elastic gas market.

The expansion of natural gas in Central Europe further displaces liquid fuel use in the household and service sectors, while the effects on the industrial sectors are negligible.

The *HP scenario* reverses the effects of the LP scenario on Central Europe, while North and South Europe maintain the gas import structure of the Base Case. By the year 2010 natural gas imports from the USSR are reduced from 146 GWyr (Base Case) to 99 GWyr, causing an identical increase in crude oil imports.

In summary, despite of the high degree of aggregation of the GATE-I model, the model's responses to a 10 percent change in gas export prices of a particular exporter are remarkable. Clearly, further analysis is required to fully comprehend the dynamics of the changes in the gas trade flows as well as the cause/effect relations of price variations on the market potential of natural gas. Furthermore, historically gas trade has been based on bilateral negotiations where the trade partners usually start off with conflicting objectives. So far there are no signs that this is going to change in the near future. Therefore it will be necessary to extend the analysis of gas trade in Europe by incorporating the multi-objective optimization approach along the lines laid out in [4].

SUPPLY SECURITY SCENARIO

Natural gas supply security considerations provide the background for another model test: the maximum gas import dependence of any Western European region on any single exporter is reduced from the Base Case value of 90 percent to 50 percent of total gas imports.

The consequence of lowering the ceiling of the gas import dependence of a region is either a price-induced or physically enforced decline in gas use. The first response reflects the fact that originally cost effective gas imports have to be replaced by other gas imports or by stepped-up domestic production, both of which are costlier than the initial gas supplies. The second reason for a reduction in regional gas consumption may be the lack of domestic resources or import diversification alternatives.

The regional responses to this import ceiling are not uniform and reflect the particular position of their energy system within the overall European context. For example, Central Europe, the largest gas consuming and importing region in Europe, purchased 68 percent of its gas imports from the USSR (Base Case). The import ceiling reduces imports from the USSR by some 40 GWyr and increases imports from North Africa (24 GWyr) to the North Sea (2 GWyr) slightly. The latter is actually the amount of gas forfeited by North Europe in order to meet its 50 percent constraint. Other adjustments of Central Europe concern an increase in domestic production by 6 GWyr and a 17 GWyr or 5 percent reduction by 2010 in gas consumption, which is a price- induced response of consumers to the higher gas price level.

The lower export potential of USSR gas to Central Europe benefits other regions. South Europe switches from North African gas (which holds a 70 percent import share in the Base Case) to Soviet gas and maintains a 50 percent balance between those two exporters. A similar switch of suppliers occurs in North Europe, but at a much smaller scale. Here North Sea gas is displaced by Soviet gas and, as already mentioned, diverted to Central Europe. And to close the circle, North African gas regains part of the market lost to the USSR in South Europe by capturing partly the USSR losses in Central Europe.

The imposed import dependence ceiling results in a restructuring of the gas trade flows. An adverse effect on gas consumption is a regional phenomenom observed only in Central Europe. All other regions maintain the level of domestic gas production and consumption. Hence, they simply switch from one exporting region to another. The present pilot version of GATE-I is still too rough a model for the detailed anlysis of the trade-offs between cost optimality and supply security. The answers to such questions will be tackled within the detailed modeling activity on international gas trade issues.

ENERGY CONSUMPTION AND ENVIRONMENTAL ASPECTS

The combustion of fossil fuels has been associated with the emissions of numerous oxides of which carbon dioxide (CO_2), sulfur dioxides (SO_2), or nitrogen oxides (NO_x) have been given special attention in public debates, mass media, etc. SO_2 and NO_x are held responsible for the adverse environmental impacts commonly labeled damage caused by acid rain. In order to gain better understanding of the order of magnitude of such emissions in the long run, Gate-1 accounts for all SO_2 and NO_x emissions along the entire energy chain, i.e. not only of the central conversion complexes but also of the transport and end-use conversion systems. In future modeling activities, especially when deploying the multi-objective approach, environmental objectives will be taken into consideration as one principal counterforce to pure cost and price objectives. Within the context of this study the potential consequences of strictly imposed emission standards on the future development of regional energy systems will be presented.

Figures 12 and 13 show the SO_2 and NO_x emissions associated with the Base Case energy consumption per region. One should note that the Base Case does not assume any environmental protection activities, and the emissions shown in Figures 12 and 13 reflect a business-as-usual situation with respect to SO_2 and NO_x emissions. The steep increases in these emissions observed during the last two decades seem to be mitigated in the Base Case. The low energy growth rates associated with a modest economic outlook, the achievements in the field of energy efficiency improvements and conservation, and the notable substitution of natural gas, nuclear, and hydropower for coal and oil products result in the reversal of the pollutant emissions in all European regions with the exception of East Europe.

Within a region the trends of SO_2 and NO_x emissions follow similar directions, but their orders of magnitude are quite different. For example, in North Europe hydro- and nuclear-generated electricity substitute for oil products throughout the regional economy. The combustion of solids remains almost constant and consequently it is possible to reduce SO_2 emissions by some 30 percent by the year 2010. In contrast, NO_x emission are reduced only by 8 percent. This is the consequence of the market penetration of natural gas which is practically sulfur-free but still produces NO_x when combusted with air.

South Europe exhibits similar trends for very much the same reasons as North Europe. SO_2 emissions are reduced more than 40 percent, while NO_x emissions decline only 1 percent. However, in 1980 North and South Europe together accounted for only 10 percent of Europe's SO_2 and 20 percent of NO_x emissions. The bulk of these emissions occurs in Central and East Europe. For example, these two regions produce jointly and in equal shares 90 percent of Europe's SO_2 releases. In the Base Case, Central Europe's SO_2 emissions decline due to the substitution of natural gas for oil use and the stagnation in coal consumption to 90 percent of the 1980 emissions. In contrast to Central Europe coal production and consumption grow in East Europe and so do SO_2 releases. By the year 2010 the SO_2 emissions of East Europe range some 45 percent above the 1980 emissions. However, the growth of a factor 1.45 is less than the primary energy growth of a factor of 1.7 over the study horizon as coal fuels only part of this expansion of primary energy use.

NO_x emissions in Central Europe decline slightly by 5 percent which clearly is a consequence of the enhanced natural gas consumption. In East Europe NO_x emissions rise by some 33 percent. This points to the increasingly lower quality of domestic coal resources this region is forced to extract in order to meet its energy supply expectations.

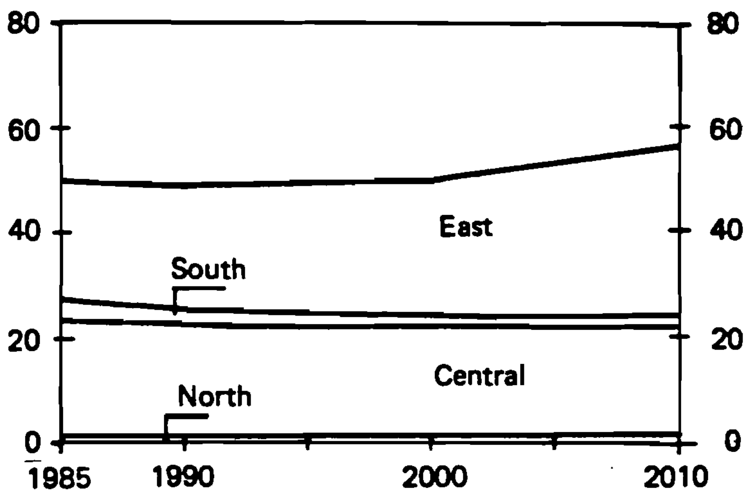

Figure 12. SO_2 Emissions, Base Case (billions tons per year).

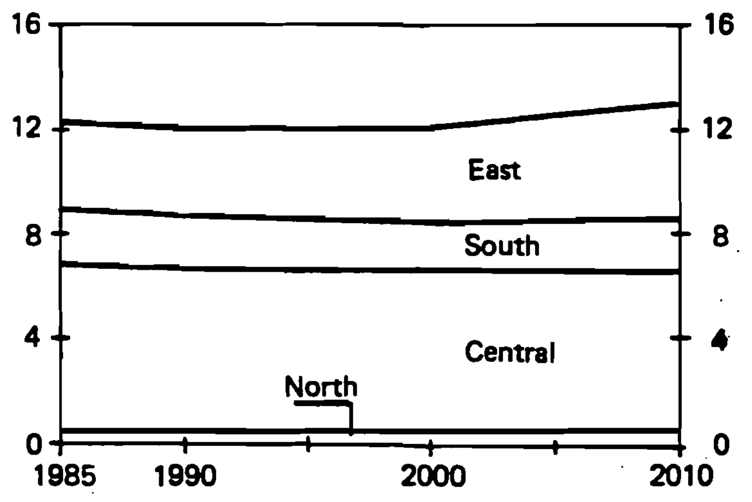

Figure 13. NO_x Emissions, Base Case (billion tons per year).

LIMITED SO_2 EMISSIONS

The following paragraphs attempt to cast some light on the role of natural gas in regional energy supplies assuming growing environmental concerns about the impacts of SO_2 releases and subsequently the damages caused by acid rain. Apart from fuel switching the model offers alternative measures for SO_2 emission reductions. All centralized fossil fuel conversion plants in industries and the electricity sector may be furnished with desulfurization equipment. The relation between costs and effective abatement results in terms of fractions of SO_2 retained are shown in Table 12.

In this test application of the GATE-I model maximum SO_2 emissions per year are imposed on the regional energy systems of Europe (see Table 13). The results of these emission ceilings with respect to the two principal options for bringing about the prescribed reductions are summarized in Table 14.

Table 14 confronts the sulfur emission for the year 2010 of the Base Case with the Limited SO_2 Case and shows the means by which these reductions are achieved, i.e. the tons of SO_2 not released to the environment by installing abatement measures and by shifts within the composition of energy consumption. The data in Table 14 indicate that about two-thirds of the SO_2 reductions originate from capital investment in abatement measures--a uniform development in almost all regions with significant fossil fuel dependence of their energy systems.

Given the higher dependence of Central and East Europe on coal, these regions face more difficulties in meeting the demanded SO_2 reductions than South or North Europe. Central Europe deploys desulfurization equipment in all major coal and fuel oil fired conversion plants. In addition, gas consumption is stepped up by 33 percent or 126 GWyr, substituting 60 GWyr for coal and 40 GWyr for fuel oil by the year 2010.

Over and above the large-scale investments in abatement equipment East Europe has to cut coal combustion significantly in order to meet the required SO_2 standards. Altogether some 160 GWyr of coal have to be replaced by other energy carriers. Similar to Central Europe, East Europe also increases gas consumption, but only to a much smaller extent, i.e. 7 percent or 17 GWyr. Contrary to all other regions oil products displace coal and grow by some 115 GWyr (70 percent increase compared to the Base Case) by the end of the study period. Parts of the investment expenditures on abatement equipment are allocated to these new oil conversion plants. Otherwise the postulated SO_2 emission levels cannot be achieved.

Compared to the Base Case, in the Limited SO_2 scenario natural gas consumption of Western Europe grows by 22 percent or 117 GWyr by the year 2010. Certainly, this increase in gas consumption will exert pressure on the domestic/regional gas markets and on the pattern of interregional gas trade.

Tables 15 to 17 depict the sources of natural gas for the different regions for the year 2010 (for comparison with Base Case data consult Tables 7 to 10). Central and South Europe add deep gas extraction to their domestic gas supply. The reduction of the 1985 level of SO_2 emissions to 30 percent by 2010 puts severe pressure on these energy systems. Conventional gas resources are already utilized in the Base Case at a maximum rate and additional imports become more and more expensive. Hence the deep gas alternative is being explored and utilized by the year 2010 and 32 and 46 GWyr are produced in Central and South Europe, respectively. The domestic gas production profiles in the other regions remain unchanged.

Table 12. Cost and Effectiveness of Desulfurization.

Limit on Desulfurization	Cost of Desulfurization	
[% of emission]	[$/kg SO_2 removed]	[mills/kWh(e)][a]
50%	0.70	2.4
80%	1.03	5.7

[a] Calculated for a coal-fired power plant.

Table 13. Limits on SO_2 Emissions (million tons per year).[a]

Region	1985	1990	2000	2010
% Reduction	0	30	50	70
North Europe	1041	739	546	347
Central Europe	22,428	15,738	11,757	7468
South Europe	3932	2808	2196	1465
East Europe	22,561	16,754	14,898	11,711

[a]Reductions are in terms of percent per unit of energy use.

Table 14. Reduction of Emissions by Type of Measure, 2010 (million tons per year).

Region	Emission Base Case	Emission Low SO_2	Desulfurization	Change of Fuel Mix
North Europe	728	347	351	30
Central Europe	20,375	7468	8266	4641
South Europe	2232	1465	508	259
East Europe	32,587	11,711	13,398	7478
Total	55,922	20,991	22,523	12,488
Percent	100	38	40	22

The gas trade pattern is modified significantly and affects all regions but the North Sea. On the exporters' side the Soviet Union and North Africa move up one category on their export price elasticity curve which results in additional gas sales on the order of 58 GWyr (up 16 percent) and 30 GWyr (up 33 percent). On the importers' side some unexpected trade flows are realized. For example, in spite of increased natural gas consumption in South Europe, the region reduces gas imports by some 22 GWyr. However, this decline in gas imports is more than offset by the newly introduced deep gas production. Furthermore, South Europe switches its external gas suppliers. Imports from the USSR are reduced by 75 percent, while North African gas increases by 10 percent. At a first glance these substitutions within the gas sector of South Europe may appear somewhat strange, but a brief impact analysis of the SO_2 constraint on Central Europe will provide sufficient evidence for this "optimal" behavior of the South European region.

Table 15. Sources of Gas, North Europe (GWyr/yr) (limited SO_2 emissions).

	1980	1990	2000	2010
North Sea	-	-	0.1	-
Soviet Union	1.2	2.9	7.7	10.0
Central Europe	-	-	0.0	-
Total	1.2	2.9	7.8	10.0

Table 16. Sources of Gas, Central Europe (GWyr/yr) (limited SO_2 emissions).

	1980	1990	2000	2010
Domestic				
Onshore 1	85.0	47.2	12.8	-
Onshore 2	35.0	53.5	79.2	96.6
Offshore 1	46.2	46.4	27.8	16.6
Offshore 2		6.1	15.8	41.1
Deep	-	-	-	31.6
Total	166.2	153.3	135.6	185.9
Imports				
North Sea	32.3	38.5	64.0	77.6
Soviet Union	22.2	76.1	143.9	210.2
North Africa	2.3	20.0	-	19.7
Total	56.8	134.6	207.9	307.5

Table 17. Sources of Gas, South Europe (GWyr/yr) (limited SO_2 emissions).

	1980	1990	2000	2010
Domestic				
Cheap	18.2	13.9	7.1	-
Expensive	-	10.0	25.o	25.0
Deep	-	-	-	46.3
Total	18.2	23.9	32.1	71.3
Imports				
Soviet Union	10.4	25.3	17.8	10.5
Central Europe	7.0	8.0	-	-
Northern Africa	3.8	10.0	86.4	94.3
Total	21.2	43.3	104.2	104.8

The large quantities of SO_2 emission reductions imposed on Central Europe forces this region not only to exhaust all additional gas import possibilities, but also to attract gas flows originally allocated for North and South Europe. The USSR gas export quantities released by South European deep gas production and import shifts are totally absorbed by Central Europe. Similar shifts but on a smaller scale occur in North Europe. Soviet gas replaces gas from the North Sea which in turn is directly allocated to Central Europe. Furthermore, Central

Europe consumes most of the additional exports from the Soviet Union. By 2010 Central Europe also resumes imports from North Africa which in all other scenarios are discontinued after the year 2000.

The reallocation of USSR and North Sea gas to Central Europe at the expense of South and North Europe, respectively, is the result of the particular objective function in the GATE-I model. The objective is to arrive at an aggregate optimum (and thus regional optima may well be disregarded). Therefore, given the adverse situation in Central Europe with respect to the fulfillment of the SO_2 constraint, Soviet gas previously exported to South Europe is diverted to Central Europe.

In summary, the Limited SO_2 scenario results in a considerably higher gas share in Western Europe's primary energy supply (33 percent) compared to the Base Case (27 percent). The numerical findings of the Limited SO_2 scenario show the potential for natural gas to alleviate the problems associated with the combustion of oil and coal. However, the increase in gas consumption as a result of SO_2 emission constraints account for only one-third of the postulated emission reductions. The remaining two-thirds require the installation of capital-intensive desulfurization equipment. At this point the model results are too preliminary to justify a deeper analysis of the trade-offs between abatement measures, fuel switching, and energy conservation.

CONCLUSIONS

The main incentive in the development of the GATE-I model was to have at hand a small but versatile mathematical tool, adequate to analyze the competitiveness of natural gas versus other fuels at burner tip. Furthermore this effort served as a pilot case in the development and application of the detailed and more sophisticated regional models. The application of GATE-I to the European regions demonstrated the operationality and usefulness of this model. Given the simplifications necessary to keep the model small and fast in its computational requirements, the main objectives have certainly been met. The numbers and interpretations throughout this paper should be seen as part of this learning and development process and therefore not be taken at face value. This pilot study left many questions open and even more questions unasked which will definitely be addressed in the coming round of research activities within the frame of IIASA's International Gas Study.

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