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Modelling Strategic Investment in the European Natural Gas Market

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1. Introduction*

This paper presents the results of a joint research project between Statistics Norway and Center for Operation Research and Econometrics (CORE), Université Catholique de Louvain. The aim of this work is to develop a gas market model for Europe. This is accomplished by combining the game theoretic supply model DYNOPOLY of Statistics Norway with the network model TEG of CORE. We use this DYNOPOLY-TEG model to analyse the future developments on the European natural gas market under three different assumptions about the market conditions in the short run TEG model. However, the focus in this paper is on the technical modelling of the gas market and less so on the applications of the model.

Some of the first attempts to model the European gas market can be found in Boucher and Smeers (1985, 1987). That work, directly inspired by Beltramo et al. (1984), relies on perfect competition mechanisms. In order to come close to the real market, it is assumed that all deviations from perfect competition can be cast into exogenous constraints and/or price margins. Various extensions of that first model were subsequently constructed. Models explicitly dealing with the imperfect competitive nature of the European gas market were initiated by Mathiesen et al. (1987) who consider three different types of competition assumptions. Computation results suggest that the European gas market can best be described by a Cournot assumption. These computational models are static in the sense that they only search for single period equilibria. They are also single stage as both investment and operations are decided at the same time. A first departure towards dynamic models was undertaken by Haurie et al. (1988). They consider a multistage development of the European gas market in an uncertain environment and search for open loop Cournot solution. While their model is dynamic, it is restricted to open loop equilibria. This limitation is removed in the DYNOPOLY model developed by Brekke et al. (1987, 1991). DYNOPOLY computes closed loop feedback equilibrium and it is thus possible to take account of strategic investment, i.e., investment where the motive is to pre-empt the opponents' investment projects. Pre-empting investment is well known from the literature[1], however, as far as we know DYNOPOLY is the only model of the European gas market which considers this aspect of investment behaviour. Other models of the European gas market have been developed in different circumstances, many of the them by consulting companies, see for instance Coopers & Lybrand (1993). The details of these models are generally not published.

The combined DYNOPOLY-TEG model presented in this paper draws on these different developments and proposes an integrated approach that expands on previous work. The DYNOPOLY model considers the European gas market in a dynamic context: producers invest in different stages and in a long run perspective. In each period there is a short run Bertrand game in prices which determines the profits of each player for given capacities. This specification of the demand side in DYNOPOLY has many shortcomings, particularly as the model incorporates no spatial dimension. This project rectifies this simplification by using the network based TEG model to calculate these short term profits for given capacities. TEG explicitly deals with the possible imperfections of the short run market by allowing one to assume different types of competition paradigms, including concerns of security of supply. Further, by looking for Nash equilibrium in the investment game described by DYNOPOLY the model also accounts for imperfect competition in the long run. The model is not limited to open loop equilibrium but explicitly aims at closed loop solutions. It is believed that this approach significantly enlarges the scope of economic assumptions that can be made for studying the European gas market. The approach is computationally flexible as it allows for the decoupling the computation

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[1] Spence (1977) and Dixit (1980) consider entry deterring investment by monopolists. Reynolds (1987) derives a feedback Nash equilibrium in investment with quadratic investment costs, and proves that the feedback solutions give more investment than the open loop solution.

of the short run and long run equilibria. This makes it possible to consider assumptions of short run competition different from those retained in this work. Needless to say difficulties remain; in particular, the approach is constrained by the inherent complexity of the computation of a closed loop Nash equilibrium. This, as well as other extensions to an uncertain environment are left as subject for further research.

The remainder of the paper is organised as follows. In section 2 we describe the DYNOPOLY model in more detail. Results from simulation on the model are presented in section 3. In section 4 we describe the DYNOPOLY-TEG model whereas a detailed description of the TEG model is enclosed in an appendix. Results from simulation on the DYNOPOLY-TEG model are presented in section 5. We look at three different assumptions about the market condition in the short run. The first scenario will be referred to as perfect competition. The second describes the situation with perfect competition with a security of supply restriction while the third scenario considers imperfect competition in the short run. The paper ends with conclusions in section 6.

2. The DYNOPOLY model

DYNOPOLY models the European gas market as a dynamic investment game. The time horizon of 80 years is divided into five year periods. In each period there is a short run Bertrand game in prices. In the literature there are several papers considering games in investments and capacities followed by a price game. Kreps and Schenkman (1983) consider a model with quantity pre-commitment followed by a price game. With a concave demand function they find that the firms charge a price that correspond to the sum of capacities, and the capacities chosen in the first stage are the Cournot capacities. The capacity pre-commitment allows the firms to make a positive profit even in the Bertrand price game. A model with investment opportunities in many periods is examined in Benoit and Krishna (1987). Under the assumption of a constant demand function over time, they find an equilibrium with no investments after the first period. However, when demand is growing over time, such as in DYNOPOLY, it may be optimal to delay investments until after the first period.

The DYNOPOLY model depicts a game between the three major suppliers to the Western European gas market: Norway, Algeria and Russia. The strategic variable is investment projects to increase the production capacity. United Kingdom (UK) and the Netherlands are not modelled as players in the game, but their production is included in the exogenous indigenous production of the demand region in the model. The elimination of the Netherlands and UK in this way reduces the number of players and thus simplifies the model. This simplification is defended on the grounds that the Netherlands has already made most of its heavy investments and production will decrease into the next century. UK has limited reserves and is not likely to become a large exporter of natural gas.

Each player in the model has up to three discrete, irreversible investment projects which must be undertaken in a specified order. At the beginning of each five year period the player can choose whether or not to invest in one or more of the remaining options. There is a five year time lag so the investments will first be operative in the following period. The moves are made simultaneously, and only previous investments are known when the players make their decisions. Production and capacity are assumed to be constant within each five year period. The capacity of a player at any point in time is thus equal to the initial production capacity plus all investment projects undertaken in previous periods. Within each five year period the price of natural gas and the profits of the three players are determined in a short run Bertrand game for given capacities. The solution to this Bertrand game implies that all players produce at full capacity.

The players maximise discounted cash flows over the entire time horizon of 80 years. This long time horizon is chosen to make sure that investment decisions of the players are not affected by an arbitrary time horizon. Further, the players have full information about demand, investment options and costs, and they can predict the other players' best responses. On the basis of this information the players choose their best strategies.

The model computes a modified subgame perfect equilibrium called a subgame perfect maximin/ Nash solution.[2] A Nash equilibrium means that in equilibrium each player's strategy must be an optimal response to he the strategies of the other players. The concept of subgame perfect equilibria was first introduced by Selten (1965). A model solution in DYNOPOLY consists of a complete plan for each player of how to act in all future periods. Since DYNOPOLY considers the closed loop feedback solutions to the game, this implies that the strategies of the players depend on both time and the state of the system, i.e., the production capacities in the specific period. Each player can then react to the actions of the other players along the optimal path as he is not committed to an investment path chosen at the outset of the game. This allows for strategic behaviour in the model[3] The players are aware that their current actions have implications in future periods and they also take account of the fact that their own actions have an impact on the actions of the other players. Undertaking an investment increases the market share of the producer, but causes a fall in the overall price. However, the other producers will foresee this price fall and might postpone new investments, and the model thus focuses on the strategic elements of the optimal investment profile. A strategic investment is defined as an investment where the only incentive for advancing the investment is pre-emption, i.e., to render the other players' investments unprofitable. In equilibrium the players will balance the profits from making an investment and thus discouraging other producers to enter their investment project, against the profits from postponing the investment and thereby restricting supply. Two tests are constructed to detect strategic investments in the simulations results. The first considers the question whether a player would delay an investment if he new the future actions of the opponents were fixed. The second test looks at whether the opponents will precipitate their investments if the player does not undertake the investment in period. This test is performed by examining the solution path in the sub-game where the first player does not enter his investment, to identify the opponents' reaction. The second test is hence useful to identify what investments the strategic player aims to discourage.

For a more thorough documentation of the DYNOPOLY model, see Brekke et al. (1987), Brekke et al. (1991) and Bjerkholt and Gjelsvik (1992).

3. Results from simulations on the DYNOPOLY model

3.1. Numerical assumptions

The demand region in DYNOPOLY comprises Western Europe excluding Sweden, Norway, Finland and Turkey. However, demand is calculated at a central point in Western Europe (the German border), thus the model does not take account of the regional aspect of the gas market. As mentioned above, the solution of the short run Bertrand game in prices implies that all players produce at full capacity. The price of gas is then determined by the equation of demand and total supply in the model.

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[2] The model is solved by dynamic programming. However, this procedure does not ensure a unique equilibrium. There may be none or many equilibria in pure strategies. We therefore introduce a modified subgame perfect equilibrium, called a subgame perfect maximin/Nash solution, where we assume that the maximin solution will be chosen in multiple equilibria situations. The maximin solution entails that a player maximise his profit given that the other players choose the worst possible actions. The experience with the model so far indicates that the lack of a unique solution in the subgames is very rare. However, the maximin solutions are more frequent in the DYNOPOLY-TEG simulation results.

[3] In open loop solutions the strategies only depend on time not on observations of the state variable. The players only have initial state information and the period of commitment is equal to the entire planning period. In feedback solutions, on the other hand, players have current state information and the period of commitment is equal to one. This solution concept is thus time consistent by construction, whereas open loop equilibria must in general be checked for time inconsistency. Time inconsistency refers to the situation where players would like to change their strategies if they could observe the current state of the system, i.e., the strategies which are optimal ex ante are not optimal ex post.

This may be interpreted as a situation with third party access (TPA).[4] Net demand for natural gas (D), which is equal to the total demand less the indigenous production of natural gas of the demand region (Q), is assumed to be a function of the producer price plus a (constant) margin which is assumed to cover transmission and distribution costs as well as taxes and profits to the transmission companies. In addition to the end user price of natural gas (P_G), demand also depends on the price of oil (P_O) and coal (P_C) and on the gross domestic product (Y) in the demand region. We assume constant demand elasticities (e1, e2, e3 and e4).

$$(1) \qquad D_t = AP_{Gt}^{e1}P_{Ot}^{e2}P_{Kt}^{e3}Y_t^{e4} - Q_t$$

The direct price elasticity is set equal to -0.927, the cross price elasticities with respect to oil and coal are assumed to be 0.365 and 0.103 respectively while the income elasticity is set equal to 0.902. These estimates are based on earlier simulations on Statistics Norway's energy demand model SEEM (Sectoral European Energy Model, see e.g. Birkelund et al. 1993). The annual growth in the gross domestic product (GDP) in the demand region is assumed to be 2.5 per cent. Further we assume a slight increase in future oil and coal prices. Both GDP and the price of oil and coal are set equal to one initially. The gross margin, defined as the difference between the end user price minus the import price on natural gas, is calculated as a weighed average over the household and industry sectors in Germany, Belgium and France. It is estimated to be $219 per ton of oil equivalents ($/toe) in 1993 (in 1990 dollars).[5]

Total supply of gas in DYNOPOLY is the sum of the indigenous supply from the demand region and the supply from the three players Norway, Algeria and Russia. Indigenous production in the demand region is assumed to be held at 1994 level of about 180 bcm/year the first two periods and approximately 150 billion cubic meter per year (bcm/year) from 2005-2010. From 2010 the production is assumed to decrease at a rate of 20 per cent over each five year period due to limited natural gas reserves in the demand region. The initial capacity of the three players is chosen exogenously. The initial production capacity takes account of existing production/export capacity as of 1995 and planned capacity to meet future deliveries under contracts that are already made at the start of the game and which will be operative from about year 2000. However, the total supply from the three players over the time horizon depends on the timing of their investments and is determined endogenously in the model. Below we give a brief presentation of the investment projects available to the three players. We assume all players use the same discount rate of 10 per cent p.a.

At the beginning of 1995 Norway had entered long term contracts for delivery of large quantities of natural gas to Western Europe into the next century. These contract volumes are included in the initial production capacity for Norway which we assume increases from 44 bcm/year in the first period to 60

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[4] TPA ensures access to the transmission pipelines by paying a specified tariff to the owner of the pipeline. This enables gas producers and end users to enter contracts of gas deliveries using the transmision companies only as a transportation service. In the European gas industry today there is a diversity of institutional framework, with monopolies co-existing with deregulated markets. United Kingdom has already adopted a system of regulated TPA, however, on the continent gas is mostly sold under long term take-or-pay contracts. The price of gas is set according to the market value principle which entails that the price is set so that gas can compete with the best energy alternative of the customer, e.g., oil, coal or nuclear power. However, the EU Energy Commission plans to create a single European gas market through TPA and unbundling. So far the process has been slowed down by the opposition from large companies in the industry, and the gas directive currently under discussion is relatively modest compared to the original draft directive put forward in 1992.

[5] The demand function is automatically calibrated with the intial supply in the model. This supply was set to equate the production capacity to the demand region in the frist period (starting in 1995). However, the initial supply in the model (336 bcm) is higher than the consumption of natural gas in the demand region in 1993 (276 bcm) according to BP(1994). Thus the prices that are simulated in the model run on Dynopoly will be too high. This will not, however, represent a problem in the DYNOPOLY-TEG model as the TEG model then calculates the profits in the short run game and thus replaces this demand function in DYNOPOLY.

bcm/year from 2000 onwards.[6] The deliveries under the long term contracts in the initial capacity involve large investments in field developments and pipeline construction. However, since these investments are required by contract, we do not consider them as part of the competition for market shares as described by the DYNOPOLY model, and hence they will not be listed as strategic investment options for Norway. Beyond the level of 60 bcm/year from 2000 we assume that Norway has two investment projects to further increase production capacity, see table 1. Both investment projects concern the development of gas fields in the North Sea area. Each investment project will add 10 bcm/year to the initial production capacity so that Norway, after having exhausted both investment options, will have a production capacity of 80 bcm/year. The first project comprises field development and investment in a new pipeline to either France or Belgium.[7] The second project assumes that gas will be delivered through the existing Frigg pipeline to St. Fergus in Scotland and thus the investment costs do not include construction of a new pipeline.[8]

The costs and additional capacity of each investment project for Norway are presented in table 1. The production costs include operating costs of pipelines and compressor stations for gas delivered to a specified point. All costs are calculated in 1990 US dollars.

Table 1. Strategic investment projects for Norway

		Capacity addition	Production costs	Investment costs
Alt.1	Low investment level	10 bcm	15.42 \$/toe to Zeebrugge 22.08 \$/toe to the German border	4.626 bill\$
Alt.2	High investment level	10 bcm	20.56 \$/toe to St.Fergus 43.87 \$/toe to the German border	1.079 bill\$

Estimates of production and investment costs are based on informal industry information. The production costs include operating costs of pipelines and compressor stations for gas delivered to a specified point. Our estimate of the transportation costs is based on the estimated tariff for transporting gas from the St. Fergus terminal to Bacton on the UK National Transmission System, then through the planned Interconnector pipeline to Zeebrugge and finally to the German border on Belgian Distrigaz's system, reported in World Gas Intelligence (1994).

Algeria has begun work on several investment projects to increase the export capacity to Western Europe by the turn of the century. As in the case of Norway these investments are not subject to the investment game depicted by the DYNOPOLY model and will not be defined among the strategic investment projects for Algeria. Rather we assume that initial Algerian export capacity in the first period is 51 bcm/year which increases to about 56 bcm/year from 2000. In addition to this initial capacity we assume that Algeria has two strategic investment projects. Both projects concern the building of compressor stations on existing pipelines, as we assume that Algeria will cap (total) LNG capacity at about 29 bcm/year. The first project deals with the installation of compressor stations on the Maghreb-Europe pipeline to Spain and will add 10 bcm/year to the initial transport capacity on this pipeline. The second project refers to compressor stations on the Transmed pipeline to increase the capacity from 24 to 30 bcm/year. The details of the two projects are given in table 2.

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[6] Norway has signed several new gas contracts since 1995. In the year 2005 Norwegian gas producers will have delivery obligations in the order of 70 bcm, see Norwegian Ministry of Petroleum and Energy (1997). However, contracts that are signed after 1995 are not included in the initial capacity of Norway in the DYNOPOLY model.

[7] Today Norwegian gas is transported to the continent through the pipelines Norpipe and Europipe to Emden and through Zeepipe to Zeebrugge. Including the Norfra pipeline to Dunkerque, which is due to be completed in 1998, the export capacity of Norway to the continent will be about 60 bcm/year. The Norwegian Ministry of Petroleum and Energy has also approved the plan for installation and operation of another pipeline, Europipe II from Kårstø to Emden, which will add approximately 18 bcm/year to the export capacity. The planned start up of the installation of Euopipe II is 1999.

[8] Since 1992 there has been a conflict between Norway and United Kingdom about the interpretations of the Frigg treaty. This has lead to the cancellation of Norwegian gas contracts with British buyers as Norway has been denied the right to transport gas thorugh the Frigg pipeline apart from the initial Frigg deliveries. However, this conflict now seems to be solved, see for example Oil & Gas Journal (1997). The Frigg pipeline has a transport capacity of 7.3 bcm/year to the gas terminal in St. Fergus in Scotland.

Table 2. Strategic investment projects for Algeria

	Capacity addition	Production costs	Investment costs
Alt.1 Compressor stations o Maghreb-Europe	10 bcm	20.14 $/toe to Spain 55.14 $/toe to Zeebrugge 61.8 $/toe to the German border	1.608 bill$
Alt.2 Compressor stations on Transmed	6 bcm	20.36 $/toe to Italy 55.54 $/toe to Zeebrugge 62.6 $/toe to the German border	0.965 bill$

Estimates are based on various sources: news information, BP (1994), Petroleum Economist (1994) and Coopers & Lybrand (1993).

The former Soviet Union (FSU) has huge reserves of natural gas and about 85 per cent of these reserves are found in Russia. It is not likely that the amount of reserves will be a limiting factor in Russian gas exports in the near future. Rather analysts are talking about a Russian «Gas Bubble», see Stern (1995).[9] We assume that the initial Russian export capacity to our demand region is about 60 bcm/year in the first period, increasing to 75 bcm/year from 2000. In addition to this initial export capacity we specify three investment projects which concern pipeline projects rather than field development projects. Of the new Russian pipeline projects the Yamal pipeline is receiving most of the media attention. The Yamal project now encompasses such a wide variety of production and transmission options that it is difficult to distinguish how many lines are being discussed, running from which fields to which destinations.[10] The «Yamal project» presented here includes the construction of two pipelines into the German border, each with a capacity of 25 bcm/year. We have, somewhat arbitrarily, split the project into two sections where each «stage» receives half the estimated costs of investment, ignoring economies of scale for multiple pipelines.

Although the focus in the media has been on the Yamal project we assume that there will be increases in Russian gas exports coming from other sources before the Yamal project will be completed. We have thus constructed a Russian investment project concerning the building of a 40 bcm/year pipeline from North Tyumen to the German border. Costs and incremental capacities are listed in table 3 below.

Table 3. Strategic investment projects for Russia

		Capacity addition	Production costs to the German border	Investment costs
Alt.1	North Tyumen	40 bcm	55.85 $/toe	8.640 bill$
Alt.2	Yamal Stage I	25 bcm	70.85 $/toe	6.809 bill$
Alt.3	Yamal Stage II	25 bcm	70.85 $/toe	6.809 bill$

Estimates are based on various sources: news information, BP (1994) and Coopers & Lybrand (1993).

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[9] Stern argues that falling internal demand will make possible the delivery of significant increments of Russian gas to Europe. He estimates that a «bubble» of Russian gas production capacity of more than 30 bcm in 1994, remained unproduced because of lack of markets, both domestic and foreign. Further, he thinks it is likely that this bubble will increase to around 40 bcm by the end of the year 2000.

[10] Stern (1995) divides the Yamal projects into four stages, starting from the customer and building backward to the reserve base at the Yamal Peninsula. The first stage is the Polish section of the pipeline laying two 56 inch pipelines from the Belarus border through Poland to the German border. The second stage includes the building of two 56 inch lines from Torzok to the Belarus border. Three 56 inch lines will be built from Ukhta to Torzok at the third stage of the project, and the last stage will finally link this new export transport system to the vast natural gas reserves at the Yamal Peninsula.

3.2. Simulations results

The results show that Algeria undertakes both investment projects, described in table 2, in 2000 see table 4.[11] However, because of the five year time lag in the model, the investments do not increase capacity until the next period so Algeria produces at maximum capacity of 72 bcm/year from 2005 onwards. Norway undertakes the first investment in 2000, while the second project is not launched until 2010. Each project adds 10 bcm/year to the initial production capacity which is 60 bcm/year from 2000. The production capacity, (and production since the solution to the short term game in the DYNOPOLY model implies that all players produce at full capacity), is then 80 bcm/year from 2015. Russia is the last player to enter the stage. The first Russian project is launched in 2005 and increases the initial production capacity of 75 bcm/year to 115 from 2010, while the two stages of the Yamal project are undertaken in 2015. From 2020 Russia produces 165 bcm/year and all producers hence produce at maximum capacity, see figure 2. As the indigenous production of natural gas in the demand region is declining after the turn of the century due to limited reserves, the region will become increasingly dependent upon imports from Norway, Algeria and Russia. The market shares of Norway, Algeria and Russia are initially 13, 15 and 18 per cent respectively. As the investment projects are undertaken and the players increase their production capacity at the same time as the indigenous production in the demand region decreased rapidly due to limited reserves, the players increase their market shares and at the end of the time horizon the market shares are 25, 22 and 51, comprising 98 per cent of total demand, see figure 1.

None of the investments are strategically motivated according to the tests described earlier. However, the simulation results on DYNOPOLY should be interpreted with some care as there is much uncertainty regarding the model assumptions. In previous work sensitivity analyses on the model have shown that the results are dependent on the particular parameter values, see Bjerkholt and Gjelsvik (1992) and Berg et al. (1997). Also, a feature of the model is that the production costs on all gas produced in any period is the same and depend on the costs specified for the last investment project undertaken. Thus the spread in the costs between the different projects and not only the level of costs is of importance when the players chose their optimal investment profile. For Algeria undertaking an investment project is assumed not to increase the level of production costs significantly, see table 2. This may in part explain why Algeria undertakes both projects in 2000 as there is no incentive to postpone the second project in order to avoid an increase in production costs on all gas produced. However, a very modest reduction in the production cost of the first project (to 60.00$/toe from 61.80$/toe) leads Algeria to postpone the second project to 2005 to enjoy the lower production costs. The same model feature may explain the delay of the second Norwegian project. Here there is a greater incentive to delay the second project in order to produce «cheap gas», see table 1. An increase in the production costs on gas until the second project is undertaken (from 22.08$/toe to 35.00$/toe) induces Norway to make the second investment one period earlier. The reason is that the spread in costs before and after the second project is undertaken is reduced, and so is the incentive to delay the investment. The same effect is observed for Russia when the production costs for the initial capacity and gas from the first project is increased. This dependence on specific cost assumptions for the different projects and the fact that reliable costs estimates are difficult to obtain, necessitate caution when explaining the investment behaviour predicted by the model.

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[11] The state of the game indicated by (1 2 0) implies that Norway has undertaken one investment project and Algeria has investested in two projects while Russia has not yet launched any of its projects. In the original DYNOPOLY model the state of the game refers to the period when the investment costs are incurred, not when the production capacity is actually increased. The investments are operative in the following period, because of the assumed time lag in natural gas investment projects.

Table 4. Simulation results in the DYNOPOLY model

Period	State of the game[1]			Capacity bcm/year			Indigenous production	Total supply	Import price $/toe[2]
	Nor	Alg	Rus	Nor	Alg	Rus			
1995	0	0	0	44	51	60	181	336	103
2000	1	2	0	60	56	75	182	373	121
2005	1	2	1	70	72	75	152	369	187
2010	2	2	1	70	72	115	122	379	240
2015	2	2	3	80	72	115	98	365	336
2020	2	2	3	80	72	165	78	395	373
2025	2	2	3	80	72	165	62	379	499
2030	2	2	3	80	72	165	50	367	624
2035	2	2	3	80	72	165	40	357	765
2040	2	2	3	80	72	165	32	349	923
2045	2	2	3	80	72	165	26	343	1101
2050	2	2	3	80	72	165	20	337	1300
2055	2	2	3	80	72	165	16	333	1525
2060	2	2	3	80	72	165	13	330	1777
2065	2	2	3	80	72	165	10	327	2062
2070	2	2	3	80	72	165	8	325	2383
2075	2	2	3	80	72	165	7	324	2744

[1] The state of the game refers to the number of investment projects the players have undertaken in that period. The investments are operative, i.e. they increase the production capacity, in the next period.

[2] The import price should not receive too much attention. The poor price prediction of the model is in part a results of the simple way in which the demand side is modelled in DYNOPOLY. This shortcoming is rectified in the next section where the simple short run game in DYNOPOLY is replaced with the network model TEG. Also, in this particular simulation run the demand for gas will be too high due to the way in which the demand function is calibrated, see footnote 6.

Figure 1. Market shares of natural gas for Norway, Algeria and Russia

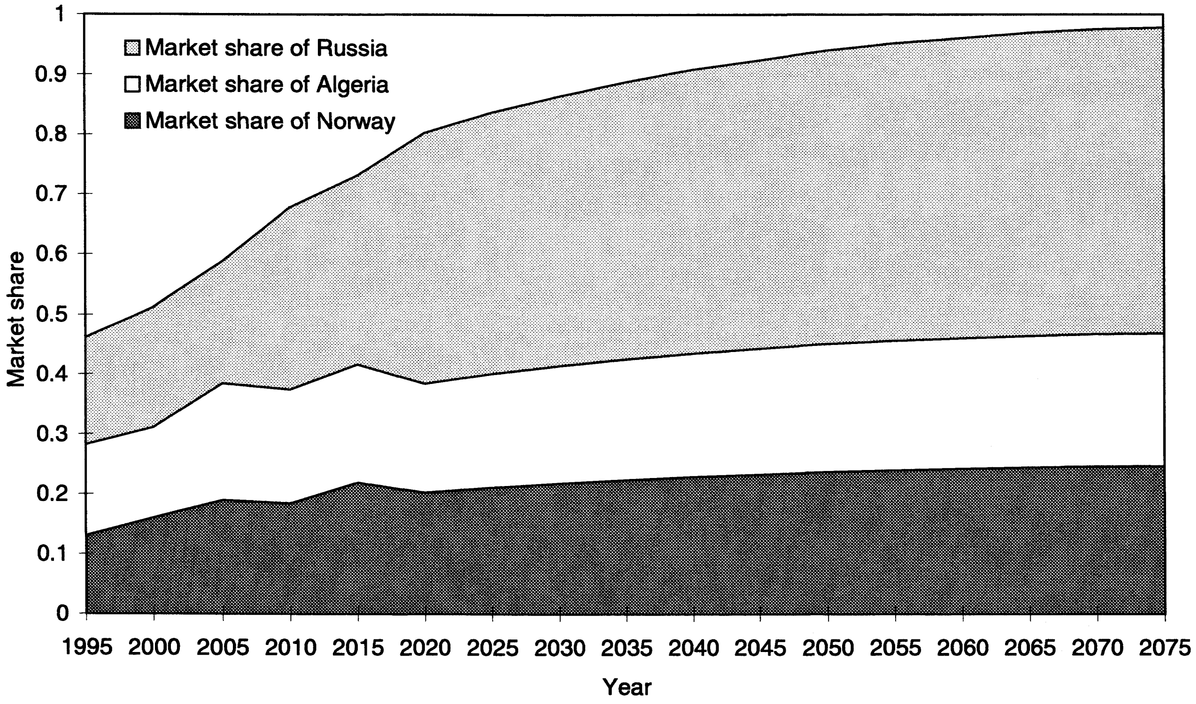
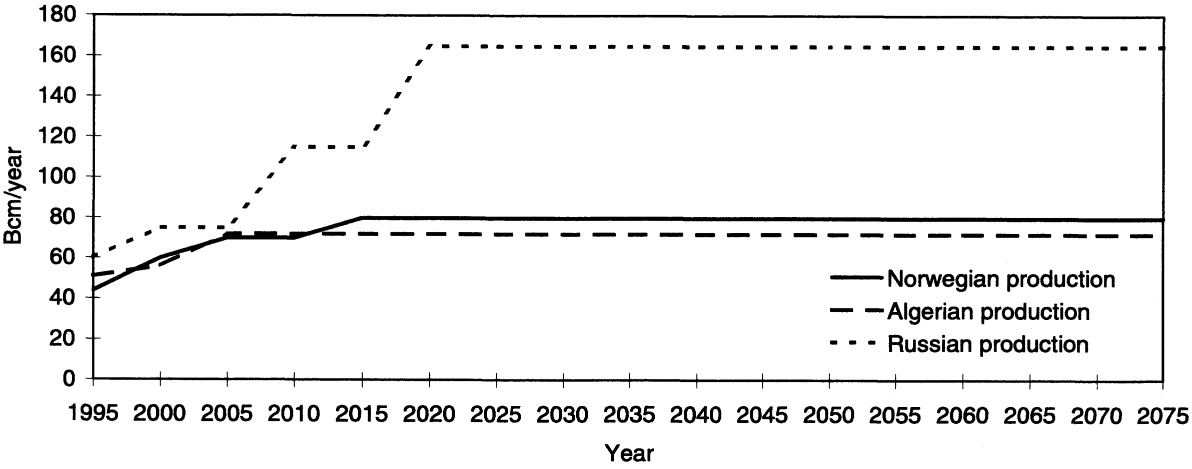


Figure 2. Production intended for the Western European market from the three players



4. The DYNOPOLY-TEG model

As mentioned above the DYNOPOLY model requires a submodel to compute profits within periods for given capacities and the solutions of the investment game depend on the solutions of this short run game. In DYNOPOLY the price and profits of each player are determined in a short run Bertrand game for given production capacities. This specification of the demand side in the model has many shortcomings, particularly the model incorporates no spatial dimension. Also, in DYNOPOLY the short run Bertrand game implies that all three suppliers produce at full capacity. However, since the price in each period is determined in a short run static game in DYNOPOLY and has no impact on later decisions, the algorithm applied in the DYNOPOLY model does not rely upon the form of this short run game. The only limitation is that the game must be numerically tractable. This study takes account of this fact as the short run profits are now determined by the network based TEG model. TEG considers the whole gas system and includes the regions where gas is produced, transported or consumed, and the natural gas system is represented as a network, i.e., as a set of nodes connected by arcs. The nodes of the network are geographical points or a set of geographical points where physical or commercial operations are carried out. The arcs represents the links between these nodes, and only through these arcs may the physical flows of gas occur. In the TEG model it is no longer necessarily the case that the gas suppliers produce at full capacity. Along with the profit data the TEG model also produces information about the rate of production and the capacity used by each producer in each state of the game and in all time periods. The production of each producer is then derived by multiplying the rate of production capacity used with the maximum capacity of the player in that period. The TEG model is described in more detail in the appendix.

The use of the TEG model to compute short run profits makes it possible to consider a whole variety of assumptions for describing the short run game. As the focus in this paper is on the presentation of the model rather that its application, we limit ourselves to briefly discuss three such paradigms. These are perfect competition, perfect competition with security of supply and Cournot behaviour. For each of these paradigms of the short term market, the TEG model generates the profits of each player in all possible states of the game and in all time periods. These profits are implemented into the DYNOPOLY model. The players now decide on their optimal investment profile subject to the profits generated by the TEG model. The three paradigms and the numerical results from the simulations on the DYNOPOLY-TEG model are presented in section 5.

5. Results from simulations on the DYNOPOLY-TEG model

As the TEG model is much more desegregated than the DYNOPOLY model, the information about costs and incremental capacity for the strategic investment projects listed above, is subject to some adjustment to fit the TEG model. Compared to the DYNOPOLY model, the production costs are desegregated into extraction costs and transportation costs depending on the pipeline used and the new projects. The extraction cost is modelled in TEG by using stepwise supply curves (found in Coopers & Lybrand, 1993). Those stepwise supply curves simulate the evolution of the extraction costs when the level of production constraints the producers to extract from more expensive fields. The profits received from the TEG model are defined as revenues from existing contracts and from the short term market minus production costs, transport costs and distribution costs and minus annuities due to new investment projects. So for the model input in DYNOPOLY-TEG we only need to specify the investment capacity of each project, see section 3.1. The costs are all taken account of in the revenue matrices from the TEG output. The revenues are in 1990 bill. ECU.

5.1. Perfect competition without security of supply restriction

Perfect competition for given capacities is the reference paradigm in market simulations. It assumes that producers and consumers do not enjoy market power. Applied to the short run gas market, it assumes that production and transport take places wherever it is justified by short run marginal production and transport cost. This does not imply that prices are equal to short run production and transportation cost as they can include a margin due to the saturation of production and transportation capacities. It is this margin, achieved on the different markets, that determines the profit made by the companies and hence ultimately, via their treatment in DYNOPOLY, their investments. Insuring perfect competition in the short run does not imply that it will prevail in the long run. In contrast with the standard perfect competition paradigm, producers can here refrain from investing in the long run in order to create scarcity rents that will in turn generate profits. The organisation of a spot market in the European gas market could very well lead to this type of situation where producers are not able to exert any market power in the short run but can still retain the possibility of strategically playing on investments. It is this economic force that we try to assess in the perfect competition paradigm.

In this scenario Algeria is the first producer to undertake investment projects. Algeria invests in both projects in 1995 so that they are operative from the period 2000, see table 5. Algeria then produces at full capacity of 72 bcm/year from 2000. Norway increases the production capacity in 2015 and 2020, while Russia is again the last supplier to undertake investments to boost production capacity. The three Russian projects are operative in 2035, 2050 and 2055 respectively. In the DYNOPOLY-TEG model it is no longer necessarily the case that the players produce at full capacity. However, only in the first three periods of the do Norway and Russia find it optimal to keep idle capacity, while Algeria produces at full capacity in the entire horizon of the game in this scenario. The production intended for the demand region in the model of each of the three gas exporters in the model is shown in figure 3. The total profits of the three players are increasing steadily as their investment projects are launched and boost their production. However, the profits of Norway and Algeria are reduced somewhat in the periods when Russia brings gas to the market from her huge investment projects and thus depresses the market price of natural gas, see figure 4.

Compared to the simulation results in the original DYNOPOLY model, presented in the previous section, the two Algerian projects are operative one period earlier in the DYNOPOLY-TEG model. Both the Norwegian and Russian projects on the other hand are postponed when the demand side of the model is extended to take account of the spatial dimension of the European natural gas market. The introduction of the different investment projects to the market is thus more spread out in time in the DYNOPOLY-TEG model. This might be explained by the spatial dimension of the DYNOPOLY-TEG model, where under the perfect competition assumption, the suppliers might have a tendency to divide the European market between them according to geographical position. In the DYNOPOLY model all three producers will compete for demand taken a specified point in central Europe, i.e., the German border. This will give Norway a cost advantage with respect to transport costs because of the geographical nearness to the German market, whereas the Algerian position towards the Italian natural gas market is not similarly taken into account.

To test for strategic behaviour in the DYNOPOLY-TEG model we have calculated a test statistic which compares the profits a producer receives if he delays the project one period holding the investments of the other players constant, with the profits he receives under the optimal investment plan.

(2) Test statistic: $\pi(t, I1)-\pi(t, I2)$

where π is the profit at time t, $I1$ is the vector of investments for the three players in the previous period and $I2$ is the optimal investment vector. When this test statistic is positive it indicates strategic behaviour. However, if a player undertakes more than one investment project in any period, then the test investigates whether these investments taken together are strategic. Therefore, in cases where we have such multiple investments we also need to study the investments separately, by comparing the profits of the producer from undertaking one investment at the time. To illustrate this point we can look at the case of multiple investments where Algeria undertakes two projects in 2000. Neither Norway nor Russia has invested in any projects at this time. The state of the game, as explained above, is then (0,2,0) in 2000, since Norway has made no investments, Algeria has invested in two projects and Russia in none. The test statistic is thus

(3) $\pi A(2000, 0,0,0)-\pi A(2000, 0,2,0) = 2.8291-3.3258 = -0.50$

Hence the two investments taken together are not strategic according to this test. However, to see whether any one of the investment considered alone might be strategically motivated we also need to look at the profits of Algeria when only one investment project is undertaken. From the results of the TEG model we find $\pi A(2000, 0,1,0) = 3.1299$. Since the profits of Algeria are higher when both projects are launched, this indicates that the reason for investing in the second project is not strategic. Similarly we check Norwegian investments for strategic behaviour. Russia, however, only invests after the two other players have exhausted their investment options, and so the Russian investments can have no pre-emptive motive. The results indicate that there are no strategic investments in this scenario.

Table 5. Simulation results under perfect competition without security of supply restriction

	State of the game[1]			Production bcm/year			Profits bill. 1990 ecu		
	Nor	Alg	Rus	Nor	Alg	Rus	Nor	Alg	Rus
1995	0	0	0	21.12	56	27	0.59	2.3	0.59
2000	0	2	0	34.8	72	44.25	0.5	3.33	0.79
2005	0	2	0	51.6	72	69	1.22	3.99	1.96
2010	0	2	0	60	72	75	5.94	9.01	11.57
2015	1	2	0	70	72	75	9.63	12.9	17.42
2020	2	2	0	80	72	75	13.15	15.14	22.13
2025	2	2	0	80	72	75	15.99	18.34	27.01
2030	2	2	0	80	72	75	19.04	21.41	31.61
2035	2	2	1	80	72	115	17.41	18.87	38.34
2040	2	2	1	80	72	115	19.43	22.24	41.65
2045	2	2	1	80	72	115	22.08	23.9	47.08
2050	2	2	2	80	72	140	21.75	22.75	52.46
2055	2	2	3	80	72	165	21.34	22.9	57.21
2060	2	2	3	80	72	165	22.61	25.23	61.46
2065	2	2	3	80	72	165	24.84	26.09	67.13
2070	2	2	3	80	72	165	26.39	28.01	71.44
2075	2	2	3	80	72	165	28.59	29.7	77.19

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[1] Because the investment costs in the DYNOPOLY-TEG model are calculated as annuities and not incurred as fixed costs one period before the investment is operative, it is convenient to define the state of the game in a slightly different way from the DYNOPOLY model. In the DYNOPOLY-TEG model the state of the game refers to when the capacity of production is actually increased, i.e. when the investments are operative.

Figure 3. The production intended for the Western European market from the three players in the DYNOPOLY-TEG model under perfect competition without security of supply restriction

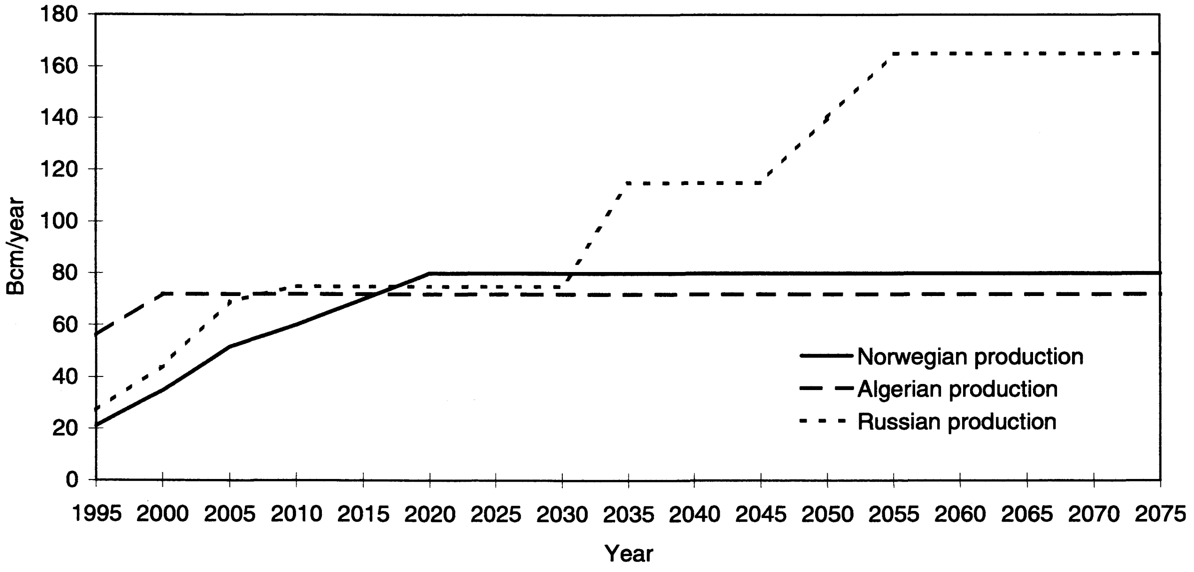
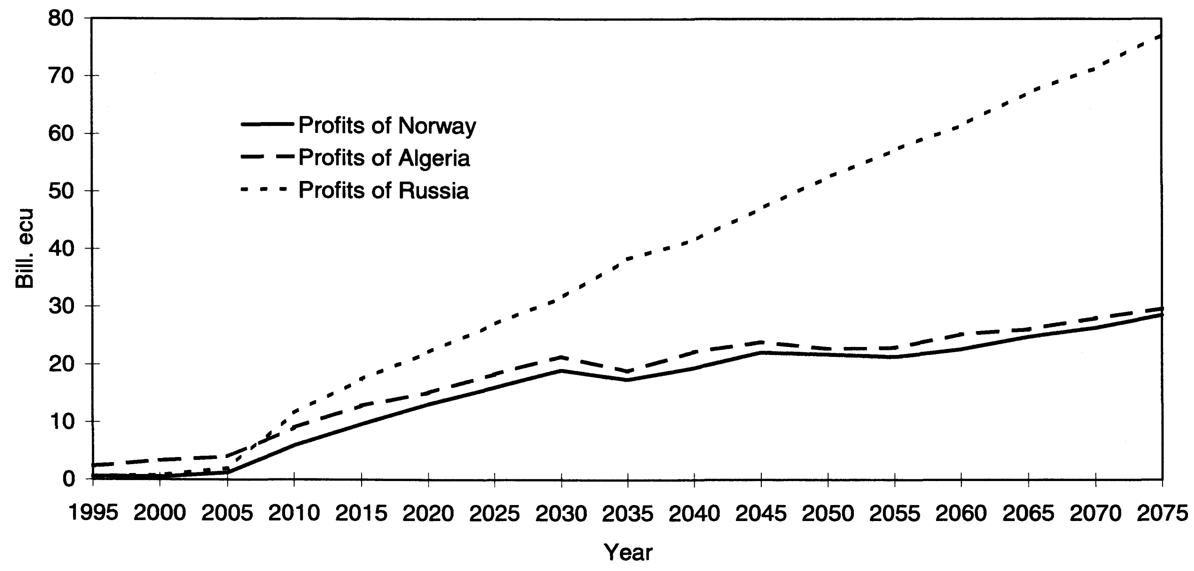


Figure 4. Profits in the DYNOPOLY-TEG model under perfect competition without security of supply restriction



5.2. Perfect competition with security of supply restriction

Security of supply is a recurrent concern in the European gas market. It is often treated by assuming that each consuming country selects its supply in such a way that no single « foreign » producer has too large a part in its portfolio of supply. It is quite possible to imagine that the preceding assumption of short run perfect competition is perturbed by concern of security of supply. This would require that bilateral contracts between producers and consumers develop and are traded in such a way that no single « foreign » consumer exceeds a given threshold level in the supply of each consumer. Supply and transport would then take place in the cost efficient way subject to the security of supply constraint. Needless to say this constraint modifies the margins that can be achieved in each single market and hence the profits achievable by each producers on the set of all markets. The organisation of the market required by this assumption is different from the one commonly assumed for spot markets. It is very much akin to the one proposed by Hogan (1993) for the transport contracts in electricity.

The fact that the European customers are concerned about the security of supply of their energy sources leads to delays in the investment activity of the exporters. All the three players postpone their investments when the security of supply constraint is activated and the last Russian project will not be undertaken in this scenario. When the consumer countries in Europe take actions to secure their energy supplies in this manner, the full potential for the Russian gas in the European market cannot be accommodated. However, the order in which the three players invest is maintained (see table 6 for further details). In the first three periods Norway and Russia operate at less than full capacity. For Russia the rate of capacity utilisation is about the same as in the scenario with perfect competition without security of supply restriction, while for Norway it is slightly higher. Algeria uses 97 per cent of her capacity in the first period and operates at full capacity for the rest of the model horizon. However, as Algeria postpones her second investment project in this scenario we might say that Algeria also takes the production cut in the early periods, see figure 5. None of the investments are strategically motivated according to the tests described above.

Compared to the scenario with perfect competition without the security of supply restriction both Norway and Russia experience a modest increase in their market shares in the early periods of the horizon. However, since the third Russian project never reaches the market in this scenario, Russia loses market shares to both Norway and Algeria from 2050 onwards. Norway and Algeria thus experience a modest increase in profits from 2050 compared to the scenario without security of supply restriction, see figure 6. With some exceptions the profits of all three players until 2050 are lower under the security of supply policy.

Table 6. Simulation results under perfect competition with security of supply restriction

	State of the game			Production bcm/year			Profits bill. 1990 ecu		
	Nor	Alg	Rus	Nor	Alg	Rus	Nor	Alg	Rus
1995	0	0	0	21.12	54.32	27.75	0.53	2.06	0.12
2000	0	1	0	39.6	66	44.25	0.75	2.66	1.23
2005	0	1	0	57.6	66	69	0.82	3.67	2.07
2010	0	1	0	60	66	75	6.11	9.95	12.91
2015	0	2	0	60	72	75	8.4	14.05	19.49
2020	2	2	0	80	72	75	12.7	15.01	21.42
2025	2	2	0	80	72	75	15.91	17.95	26.96
2030	2	2	0	80	72	75	18.91	20.81	31.94
2035	2	2	0	80	72	75	21.41	23.62	37.03
2040	2	2	1	80	72	115	19.24	21.02	41.99
2045	2	2	1	80	72	115	21.92	23.79	46.93
2050	2	2	1	80	72	115	23.71	25.01	51.39
2055	2	2	1	80	72	115	24.99	27.27	55.22
2060	2	2	2	80	72	140	25.86	27.65	58.47
2065	2	2	2	80	72	140	27.23	30.36	61.71
2070	2	2	2	80	72	140	29.49	31.44	65.21
2075	2	2	2	80	72	140	29.84	32.15	68.12

Figure 5. The production intended for the Western European market from the three players in the DYNOPOLY-TEG model under perfect competition with security of supply restriction

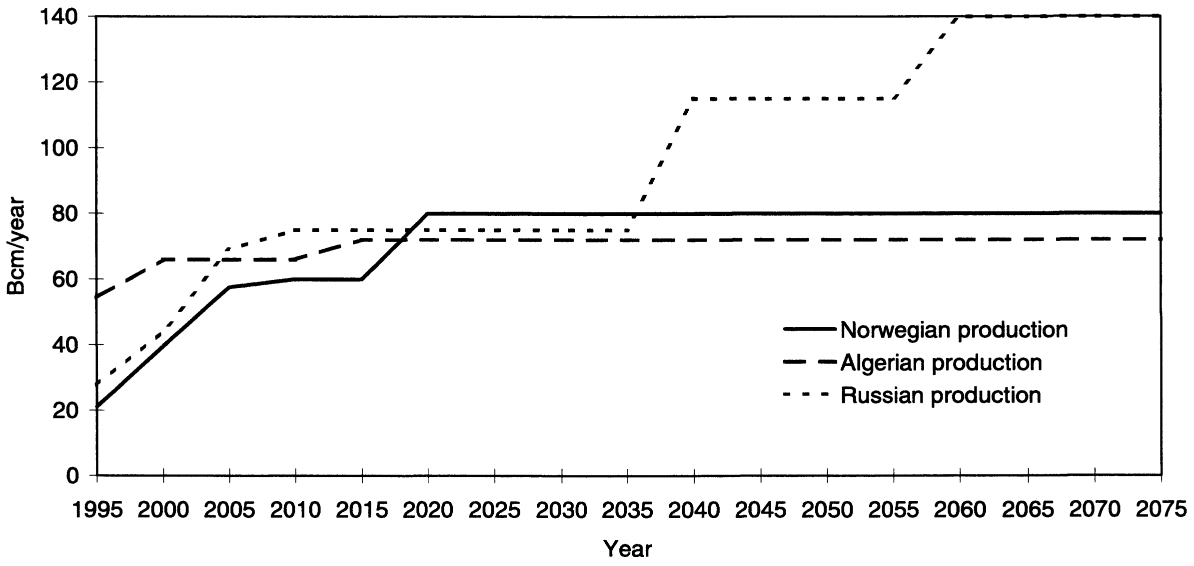
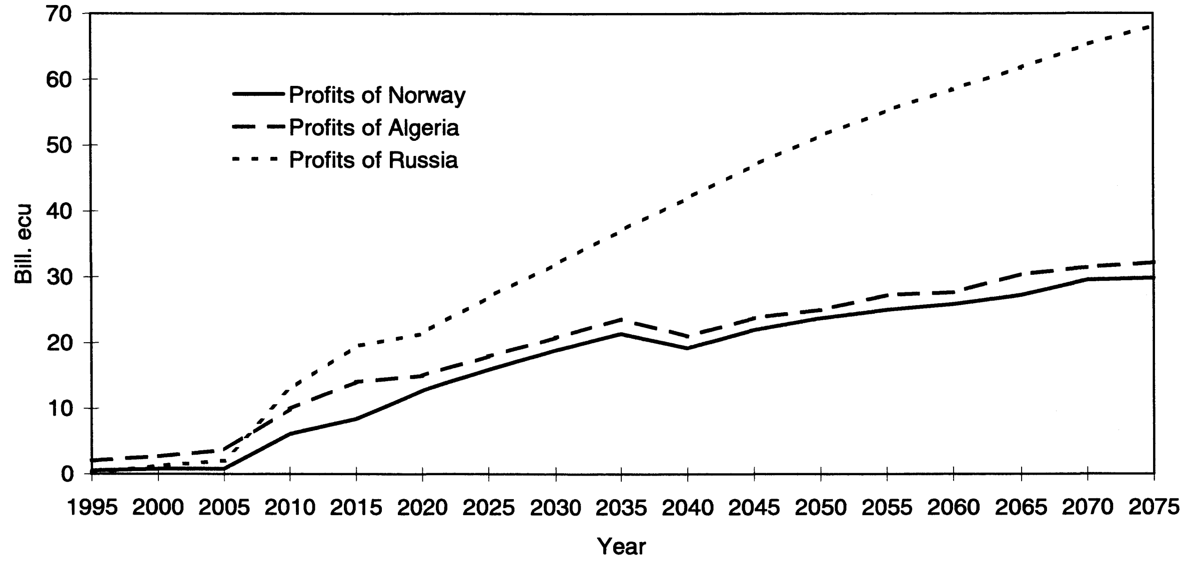


Figure 6. Profits in the DYNOPOLY-TEG model under perfect competition with security of supply restriction



5.3. Imperfect competition

The last paradigm of competition tested in this work is a spatial version of Cournot competition in the short run game for given capacities. This assumption is now standard and is frequently seen as the most natural departure from perfect competition. It has been found quite relevant for describing the European gas system (see Mathiesen et al. (1987) and more recently Golombek et al. (1995)) and it is likely to remain so to the extent that the number of significant producers in the European gas market will remain small for quite a lot of time. It also constitutes a further step away from the spot market. In this model gas trade is still described by bilateral deals between producers and consumers but they cannot be resold on a secondary market. The need to represent bilateral contracts both in this and the previous versions of the model has technical consequences. Because the TEG model assumes a full network representation of the European gas market, bilateral deals cannot be represented in a natural way within the physical description of the trunklines underlying the European gas system. Additional complications need then be introduced in order to cast this bilateral deals in the network representation. This is described in the appendix.

When we assume Cournot competition on the supply side in the TEG model the order in which the players launch their respective projects is altered compared to the two previous perfect competition scenarios, see table 7. Russia now invests in all three projects so that they are operative in 2000. This entails the postponement of the second Algerian project until 2010, while the Norwegian investments will not be undertaken until 2030 and 2050 respectively. The introduction of imperfect competition thus leads to higher market shares for Russia at the expense of both Algeria and Norway until 2050 compared to the situation with perfect competition without security of supply restriction. However, although Russia has the maximum production capacity of 165 bcm/year available from 2000, Russia never actually produces this full amount. Russia uses as little as 17 per cent of the capacity in 2000. Norway and Algeria also find it optimal to keep idle capacity in this scenario. However, the rate of capacity utilisation of the three players increase over time and Algeria operates at full capacity in the three last periods of the model horizon, see figure 7. In terms of market shares all three players lose market shares in the early periods compared to the scenario with perfect competition without security of supply. However, Russia gains market shares from 2010 and Algeria also experience somewhat higher market shares in the later periods from 2040. In terms of total net revenues, however, all three players gain under imperfect competition relative to the perfect competition scenario, see figure 8. The tests described earlier indicate that the introduction of the third Russian project is strategically motivated in this scenario. Although the three Russian investments taken together are not strategic, a closer look at the Russian profits indicates that the third Russian investment project is brought on market in 2000 to serve strategic intentions[12] None of the investments of the other players appear to be strategically motivated.

Table 7. Simulation results under imperfect competition

	State of the game			Production bcm/year			Profits bill. 1990 ecu		
	Nor	Alg	Rus	Nor	Alg	Rus	Nor	Alg	Rus
1995	0	0	0	8.36	21.84	7.5	5.81	23.58	10.57
2000	0	1	3	10.2	29.7	28.05	7.56	24.81	21.54
2005	0	1	3	19.8	29.04	37.95	13.91	25.3	32.51
2010	0	2	3	29.4	29.52	52.8	11.6	18.22	51.37
2015	0	2	3	24.6	30.24	74.25	18.31	17.81	54.29
2020	0	2	3	30.0	32.4	80.85	20.12	26.61	58.82
2025	0	2	3	30.0	40.32	89.1	18.27	32.87	45.06
2030	1	2	3	32.9	40.32	99	24.45	26.9	71.5
2035	1	2	3	49.7	45.36	95.7	20.81	36.59	71.46
2040	1	2	3	56.0	58.32	100.65	22.54	40.7	75.73
2045	1	2	3	37.8	54.0	123.75	14.32	36.25	96.03
2050	2	2	3	56.8	67.68	110.55	34.41	21.84	100.38
2055	2	2	3	65.6	65.52	122.1	35.86	45.89	87.11
2060	2	2	3	68.8	69.12	127.05	28.21	34.53	117.73
2065	2	2	3	64.0	72	135.3	28.27	37.71	124.54
2070	2	2	3	65.6	72	145.2	37.66	39.75	133.92
2075	2	2	3	75.2	72	153.45	32.52	40.15	136.55

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[12] In 2000 Norway has not invested while Algeria has invested in her first project. The profits of Russia in the different states in period 2000 are as follows: $\pi R(2000, 0,1,0) = 16.8944$, $\pi R(2000, 0,1,1) = 26.3702$, $\pi R(2000, 0,1,2) = 30.6762$ and $\pi R(2000, 0,1,3) = 21.5382$. According to the test the three investments taken together are not strategic as $\pi R(2000, 0,1,0) - \pi R(2000, 0,1,3) = 16.8944 - 21.5382 = -4.6438$. However, we see that the introduction of the third project actually lowers the profits of Russia compared to the state where Russia invests in only two projects. This indicates that the third Russian project is launched for strategic reasons.

Figure 7. Production intended for the Western European market in the DYNOPOLY-TEG model under imperfect competition

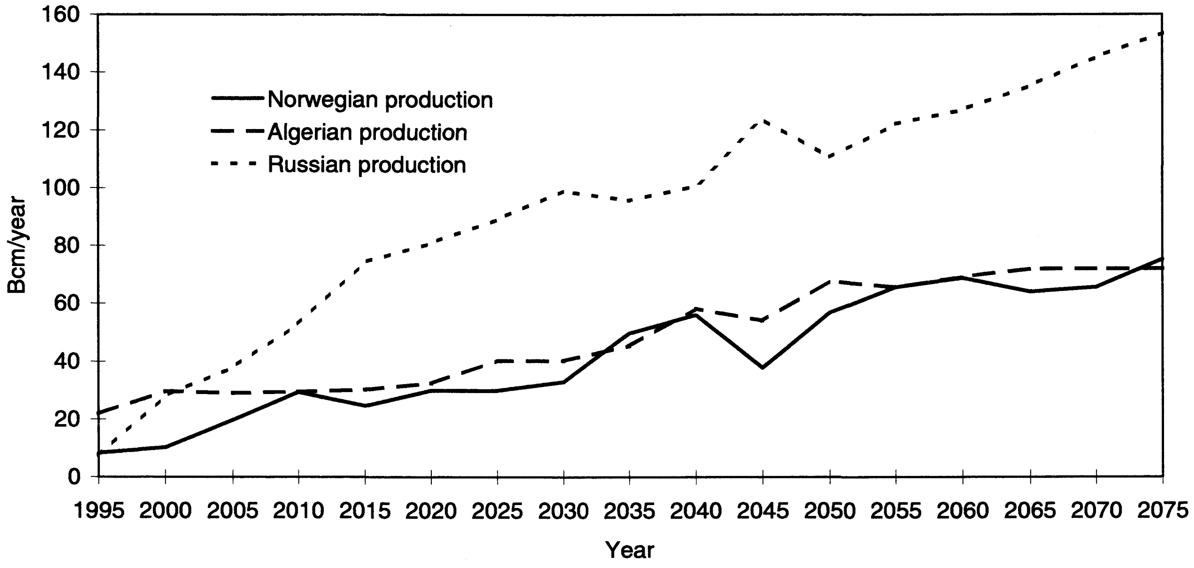
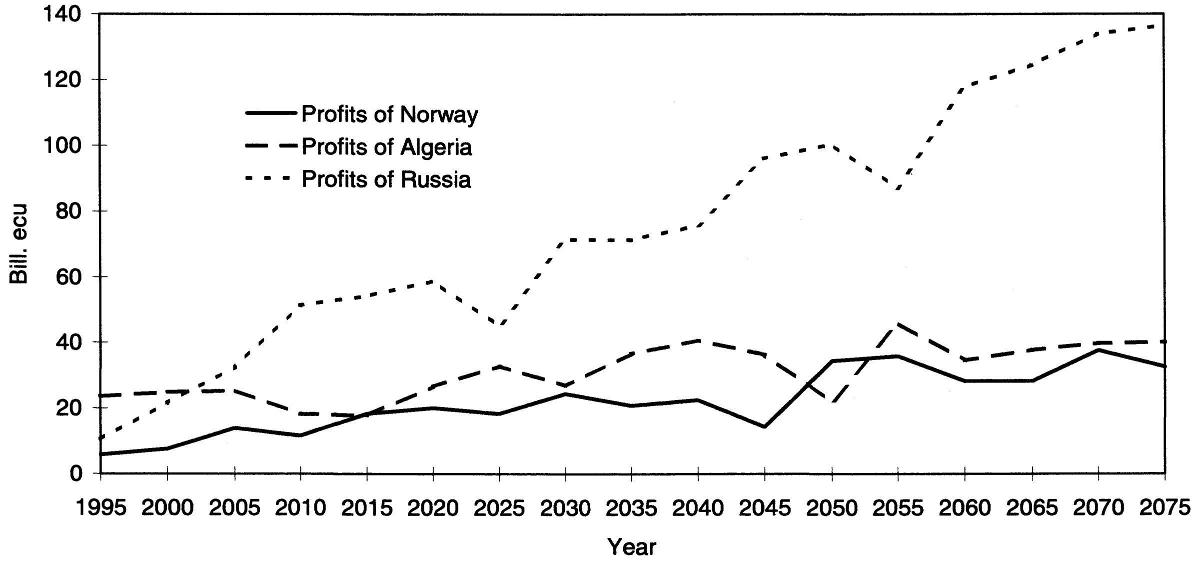


Figure 8. Profits in the DYNOPOLY-TEG model under imperfect competition



6. Conclusions

In this study we have developed a model for the European natural gas market combining the two models DYNOPOLY and TEG, developed by Statistics Norway and CORE respectively. The DYNOPOLY model considers the European gas market in a dynamic context where producers invest in different stages and in a long run perspective. DYNOPOLY computes closed loop/feedback solutions and the model thus focuses on strategic investment behaviour in the European gas market. In each period there is a short run Bertrand game in prices which determines the profits of each player for given capacities. This specification of the demand side in DYNOPOLY has many shortcomings, particularly the model incorporates no spatial dimension. However, in this project we rectify this simplification by using the network based TEG model to calculate these short term profits for given capacities. TEG explicitly deals with the possible imperfections of the short run market by allowing one to assume different types of competition paradigms, including concerns of security of supply. The approach is computationally flexible as it allows for the decoupling the computation of the short run and long run equilibria.

We illustrate the application of the DYNOPOLY-TEG model by presenting numerical results from model simulations under three different assumptions about the market conditions in the short run TEG model. These are perfect competition, perfect competition with a security of supply restriction and imperfect competition. However, it is possible to consider assumptions of short run competition different from those retained in this work.

The empirical results from the simulations performed in this study indicate that the Russian investment projects are most sensitive towards changes in market assumptions. According to our results the Algerian projects will be undertaken by the year 2015 regardless of the model assumptions about the demand side. It is the Russian projects that are displaced and delayed the most when the security of supply constraint is activated. However, Russia also gains the most when we introduce imperfect competition on the demand side, in which case all the Russian projects are operative in 2000. Both the Norwegian investments will be undertaken by 2020 under perfect competition, but delayed until 2030 and 2050 under imperfect competition. In the simulations on the DYNOPOLY-TEG model we only detected one investment that was strategically motivated; the third Russian investment undertaken in 2000 under imperfect competition. One possible interpretation of the fact that we do not observe more strategic investment behaviour in the model simulations is that the suppliers already have contracted large amounts of gas which are included in the initial capacity of the three producers. The European natural gas market is hence a more mature market than in the 1980ies. Earlier simulations on the DYNOPOLY model have revealed more strategic behaviour, see Bjerkholt and Gjelsvik (1992).

However, because of certain problems which makes the computations of the model solutions in TEG very time consuming and tedious, we have not been able to perform sensitivity analyses as to the robustness of the results in the short run TEG model. Previous sensitivity analyses on the DYNOPOLY model have indicated that the numerical results in DYNOPOLY are highly dependent on the specific parameter and cost assumptions made. In the simulation results on the DYNOPOLY-TEG model there is also a more frequent occurrence of maximin solutions in the dynamic investment game.[13] As mentioned in the presentation of DYNOPOLY the model is solved by dynamic programming. However, this procedure does not ensure a unique equilibrium and we assume that the maximin solution will be chosen in situations with multiple equilibria. With many such maximin solutions in the optimal investment path it is more difficult to interpret the equilibrium concept.

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[13] In the simulation on the DYNOPOLY model in section 3 there is only one maximin solution. Whereas in the model runs on the DYNOPOLY-TEG model there are 54, 52 and 217 such maximin solutions in the three scenarios respectively, also see footnote 3.

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The TEG model

This appendix describes the TEG model. It represents the physical and commercial flows of gas involved in the following processes:

- gas extraction,
- liquefaction of natural gas,
- gasification of the liquefied gas,
- gas transportation through pipelines or LNG tankers,
- commercial transactions relative to the gas,
- gas consumption.

1. Data structures of the TEG model

This chapter describes the data structures of TEG.

The gas system is represented in TEG as a network. Its components and temporal and spatial characteristics are first presented, then their interactions with the physical and commercial operations involved in gas production and trade are explained. The next section focuses on the agents that are acting on the gas market and on their relations with the gas network and its physical operations. The possible transactions between the agents are finally described, as well as the regulations that apply to the transactions.

1.1. The temporal framework

The model horizon is composed of a set of periods. The length of the periods is 5 years. In this work each perdiod is run indepedently of the other with given exogenous capacities.

1.2. The spatial framework

The model considers the whole gas system. This includes the regions where gas is, or will be potentially, produced, transported or consumed.

1.3. The transportation network

The natural gas system is represented as a network i.e. a set of nodes connected by arcs. The nodes of the network are geographical points or a set of geographical points where physical or commercial operations are carried out on gas. The arcs represent the links between these nodes. Only through these arcs may the physical flows of gas occur.

1.3.1. The operations at the nodes

We separate the operations at the nodes in two classes: the physical operations and the commercial operations.

1.3.1.1. The physical operations

Gas extraction
Gas extraction takes place at gas fields. A gas field is located at some node of the network. At this stage, the fields will be characterised by their maximal yearly production level, their production cost and their reserves. The maximal yearly production level is the result of technical, financial and political constraints.

We have two types of producers: the exogeneous suppliers and the endogeneous ones. For each type, the production costs are described by a stepwise supply curve (from Cooper & Lybrand).

Gas liquefaction
Gas liquefaction is carried out by cryogenic processes. It allows gas transportation in specially designed tankers which referred to as LNG tankers. Liquefaction occurs at a liquefaction terminal. Apart from the liquefaction plant itself, the terminal also includes shipping facilities for the LNG tankers.

A liquefaction terminal is characterised by a yearly processing capacity, a variable cost and an efficiency. The capacity limitation represents both the capacity limitation of the liquefaction plant itself as well as that of the shipping installation.

Liquefied gas gasification
At this stage we consider as a whole the following operations: LNG tankers unloading, gas storage, compression and gasification. The operations are supposed to occur in a gasification terminal. A gasification terminal is characterised by a yearly processing capacity, a variable cost and an efficiency. The capacity limitation represents both the capacity limitation of the gasification plant as well as that of the receiving installations.

Gas storage
A representation of seasonal gas storage in the TEG model is not usefull because of temporal framework.

Gas compression
The only representation of gas compressors in TEG is achieved by giving an efficiency and a capacity for each arc. We do not have a real representation of compressors behaviours.

Gas consumption
Gas consumption refers to the operations whereby natural gas undergo chemical processes (including combustion) that convert it, totally or partially, in substances of another chemical nature. We do not include in those operations those that are necessary to production and transportation, i.e., re injection of gas in fields, gas necessary for the propulsion of LNG tankers, etc.

Gas consumption is the fact of consumers. They are generally spread throughout the territory that the model encompasses. The model aggregates them in consumption sectors that have a precise location in each country or region. These locations are nodes of the network. The consumptions are endogeneous and defined by a linear demand curve for each consumption sector and in each node. The elasticities were found in the Cooper&Lybrand report (« Commission of the European communities West European Gas Study and Model Final report: Volume II-The model. », August 1993, Cooper&Lybrand. p. 78).

1.3.1.2. The commercial operations
The commercial operations refer to transactions. We consider two types of transactions: the merchant transactions (gas sales and purchase) and the service transactions (transmission). The service transactions always involve some transport or transmission facility.

Two instruments are available for the transaction. Long term existing contracts and spot deliveries. The contracts are exogeneous so that no new contract could be signed. Their characteristics are the selling company, the bying company, the input node, the output node, the route taken by the transaction, the delivery price, the duration of the contract and of course the amount of gas to be deliver (eventually combined with a flexibility).

None of those characteristics defines the spot market. All those clauses are totally free.

1.3.2. The arcs

The model considers two types of arcs: the pipelines (or sets of parallel pipelines) and the LNG routes.

1.3.2.1. The pipelines

The pipelines can be one-way or two way arcs.

Transportation through a pipeline is limited by some yearly capacity and it involves costs and losses. The capacity constraint is determined by the section and the operating conditions of the pipe system. The losses are caused by mechanical imperfections as well as by the powering of the compressor stations when these are not represented in detail in the model.

1.3.2.2. The LNG routes

From a liquefaction plant to a gasification plant, LNG is transported by tankers. An LNG route is the path taken by the tankers from a liquefaction plant to a gasification plant. LNG routes are one-way arcs. They can only go from a node with a liquefaction terminal to a node with a gasification terminal.

Transportation of LNG involves a variable cost and losses. The losses are mainly due to the powering of the tankers.

At this stage, we assume that each liquefaction terminal has a distinct fleet of LNG tankers that ship the liquefied gas from the terminal. Only those tankers can board at the liquefaction terminal. The tankers may be assigned to any route that starts from the liquefaction terminal. We also assume that the capacity of the fleet of tankers does not depend on the length of the routes taken by the tankers. Therefore, the capacity limitation of the terminal will have to take into account the capacity of the fleet of tankers that ship the LNG from the liquefaction terminal. Also, we do not consider capacity limitations for LNG routes since they are already accounted for in the constraint on the gas which is liquefied by the terminal at the origin of the arc.

1.4. The actors on the gas market

1.4.1. The consumption sectors

Consumers are aggregated in consumption sectors. The degree of aggregation may vary from country to country. Consumption sectors are located at nodes.

The consumption sectors are price takers on the gas market. Their behaviour is represented by their gas demand curve. This curve gives the total demand of the consumption sector as a function of the gas price to that sector. The consumer gas price includes distribution costs, excises and taxes.

1.4.2. The companies

The model considers several companies that are acting on the gas market. Each company may own gas fields, liquefaction terminals, gasification terminals, gas storage facilities, compressor facilities and arcs. It may also own a part of the previous installations, the rest being owned by other companies. A company may have an exclusive right to serve some demand sectors. It will certainly be the case for european companies which have in TEG exogeneous production.

The companies may carry out the following physical actions:
- extract gas from fields,
- liquefy and gasify gas,
- transport natural gas in liquid or gaseous form.

If a company only owns or rents a share of one of the previous installations, it may use the corresponding part of the total capacity of the equipment independently of the actions of the other owners of the equipment.

In what follows, we will call "capacity" any part of the total capacity of an equipment.

Companies may also set up new equipment capacities but those are exogeneously given.

The companies may also engage themselves in transactions with other economic agents. These transactions are:
- selling or buying gas from other companies,
- selling or buying liquefaction and gasification services,
- selling or buying transportation services,
- serving consumers,

The prices and the quantities that these involve result from a bargaining process. That may be subject to regulation.

The companies earn revenues from selling gas as well as from the services they offer on all their equipments. They pay the costs of the equipments that they own and their purchases of gas or services from the other companies.

2. The different gas supply models in TEG

A single mathematical framework, namely mathematical programming, is used to specify the relations between the elements described in chapter 1. However, different assumptions on the behaviour of the agents and different levels of desegregation lead to different behavioural equations for these agents and, therefore, to different models. This chapter surveys these assumptions and the levels of desegregation. Then it elaborates on the consequences on the model formulation.

2.1. Behavioural assumptions

2.1.1. Trade

This section characterises the different assumptions on the behaviour of the agents that are acting on the market.

2.1.1.1. Trade between companies

Perfect competition

Under the perfect competition assumption, no company has a sufficient market power to influence price levels. Each company considers therefore prices as given in its profit maximisation process.

Equilibrium is under those circumstances found at the intersection of supply and demand curves. A well known result of microeconomic theory establishes that this equilibrium point also corresponds to the point where the producers' and consumers' surplus is maximised. This further allows to compute the competitive equilibrium in the underlying gas market through the solution of a mathematical program.

Imperfect competition: a Cournot model
The restricted number of companies (namely Russia, Algeria and Norway) that are acting on the gas market and the character of natural monopoly that prevails in the gas transportation activity justify that non competitive behaviours be considered.

In the imperfect competition formulation, the behaviour of the agents is modelled company by company. Since the companies are profit maximisers, their actions can be found under the form of a mathematical program whose objective is profit maximisation. In contrast with the perfect competition case, the search for equilibrium requires that a set of mathematical programs be solved iteratively.

2.1.1.2. Trade between companies and consumption sectors

Consumption sectors
The consumers are price takers on the market.

Companies
The behaviour of the companies in their relations with the consumption sectors depends on the European and national regulatory rules. Hence it may vary from country to country. Also, the degree of competition that is allowed to occur between companies for the service of a market may vary from a consumption sector to another.

Perfect competition
Under this assumption, some or all companies are allowed to serve some or all consumption sectors. Companies are assumed not to have sufficient market power to influence prices.

Perfect competition at sales may only occur if trade between companies is perfectly competitive.

Imperfect competition between several suppliers
Under this assumption, some or all companies are allowed to serve some or all the consumption sectors. Their limited number justifies that non competitive behaviours be considered. This assumption does not encompass the monopolistic situation, which is covered in the next section.

Imperfect competition at sales may only occur if the trade between the companies is not competitive.

Monopoly
This corresponds to the current situation. It is justified by the character of natural monopoly that prevails in the transportation activity. Regulation may impose special tariffing rules however.

Monopoly at sales may occur whatever the assumption that is retained on the degree of competition in trade between companies.

2.1.2. Security of supply
In order to improve the security of their supplies, several companies may decide to pool their reserves in case of shortage. We call this group of companies a security group. When a company does not make such agreements, we consider that it is a security group by itself. This corresponds to the current situation.

Security groups may aim to secure a diversified portfolio of suppliers. If they do so, they require that the total amount of gas that the member companies purchase from any single supplier be lower than a given fraction of the group's sales of the group to the other companies or to the consumption sectors. These restrictions bear on long term agreements only. They do not deal with short term exchanges

2.2. The gas flows in the model

The models consider two types of flows: physical flows and commercial flows. Physical flows correspond to gas moves within some installation (pipeline, LNG plant, storage facility, ...). A capacity constraint in a pipe-line is due to a physical flow. They may exist on the arcs or at the nodes. Commercial flows correspond to changes of property. A commercial flow is indexed by the selling and the bying company.

We always consider that the value of the flow is the amount of gas that flows in the node or in the arc. To obtain the quantity of gas that flows out the arc or the node, one needs therefore to substract possible losses.

3. Mathematical Formulation Of The TEG Model

3.1. The data of the main database

3.1.1. The temporal framework

3.1.1.1. The sets

YEAR	Years of the horizon;

3.1.2. The actors

3.1.2.1. The sets

COUNTRY	Countries modelised in TEG;
CIE	Gas companies modelised in TEG;
SECTOR	Consumption sectors;
$\text{NODEtoCC}_{\text{node,country}}$	Link between a node and a country;
$\text{NODEtoCIE}_{\text{node,cie}}$	Link between a node and a company;

3.1.2.2. The parameters

$\text{DISTRdesc}_{\text{country}}$	describes the transport and distribution costs [ECU/BCM/YEAR]
'trans'	transport cost
'distri'	distribution cost
$\text{GASdemand}_{\text{country,sector,year}}$	Reference gas demand for each sector of a country [Mtoe]
$\text{GASprice}_{\text{country,sector,year}}$	Reference gas price for each sector of a country [ECU/Mtoe: tax included]
$\text{ELAS}_{\text{country,sector,year}}$	Gas demand elasticity price for each sector of a country
$\text{DEMrep}_{\text{node,country}}$	Repartition of the national demand on the nodes associated to that country
$\text{SECU\_RATE}_{\text{country,cie}}$	Maximum allowed gas importation from a company.

3.1.3. The network description

3.1.3.1. The sets

NODE	Node of the network. These nodes represent production nodes, transmission nodes, distribution nodes or consumption nides;
PIPE	The pipelines are oriented arcs connecting two nodes. They have a efficiency, a capacity and one or more owners;
$\text{LINKnDEP}_{\text{node,pipe}}$	Link between a node and a leaving arc;
$\text{LINKnARR}_{\text{node,pipe}}$	Link between a node and a arriving arc;

3.1.3.2. The parameters

$\text{PIPEown}_{pipe,cie}$	Share of a pipeline owned by a company;	
TRANSdesc_{pipe}	Gives some characteristics of the pipeline	
'eff'	pipeline efficiency	
'capa'	pipeline capacity	[BCM/YEAR]
'cost'	transit cost	[ECU/BCM/YEAR]

3.1.4. The contracts

3.1.4.1. The sets

CONTRACT	Existing long term contract between a producer and a distributor

3.1.4.2. The parameters

$\text{ECprice}_{contract}$	Purchase price of the contract [ECU/BCM/YEAR]
$\text{ECdepXX}_{contract,node}$	Describes the contract path: link between contracts and nodes. For facility reasons, the contracts are regrouped in one table by contracts leaving the same country.
$\text{ECamount}_{contract,year}$	Gives the annual amount of gas delivered by year and contract [BCM]

3.2. The Model Sets, Parameters & Variables

The sets and parameters specially defined for the model are the following:

3.2.1. Sets and Parameters Defined to Simplify the Model Notation

$\text{ECtoPIPE}_{contract,pipe}$

desc: Automatic link between a Existing contract and a pipeline
unit: 1 for existing link 0 if none

$\text{PIPEtoNODE}_{pipe,node}$

desc: Automatic link between two adjacent nodes and a pipeline
unit: - 1 for the origin of the pipeline
+1 for the destination of the pipeline

$\text{ECdep}_{contract,node}$

desc: concatenation of the different ECdepXX table
unit: none

$\text{CtoBUYcie}_{contract,cie}$

desc: Links an existing contract with the purchasing cie
unit: 1 if the Cie buys electricity from another CIE

$\text{CtoSELcie}_{contract,cie}$

desc Links an existing contract with the selling cie
unit 1 if the Cie sells electricity to another CIE

$\mathrm{PRICEval}_{country,sector,linea,year}$

desc: linearisation segments
unit: [BCM]

$\mathrm{LOADVAL}_{country,sector,year}$

desc: Division of demand into segments for linearisation of demand function
unit: [BCM]

3.2.3. The model variables

The decision variables of the model are the following:

$\mathrm{FLOW\_FORW}_{cie,cie,pipe,year}$

desc: short term contract gas flow in pipeline in the forward size
the first described cie is the selling cie
the second one is the purchasing cie
unit: [BCM/year]

$\mathrm{FLOW\_BACK}_{cie,cie,pipe,year}$

desc: short term contract gas flow in pipeline in the forward size
the first described cie is the selling cie
the second one is the purchasing cie
unit: [BCM/year]

$\mathrm{QAF}_{pipe,year}$

desc: physical gas flow in pipeline in the forward size
unit: [BCM/year]

$\mathrm{QAB}_{pipe,year}$

desc: physical gas flow in pipeline in the backward size
unit: [BCM/year]

$\mathrm{FLOWcont}_{pipe,contract,year}$

desc: long term contract gas flow in pipeline by contract
unit: [BCM/year]

$\mathrm{EXTRACTION}_{cie,cie,node,year}$

desc: gas extraction at node
unit: [BCM/year]

$\mathrm{LOSS}_{cie,cie,node,year}$

desc: gas loss at node
unit: [BCM/year]

$CONSUMP_{cie,cie,country,sector,year}$

desc: Gas delivery by a cie for consumption by country and economic sector
unit: [BCM/year]

$SEGMENT_{country,sector,linea,year}$

desc: segment in linearisation of gas consumption
unit: [BCM/year]

$CIEobj_{cie,year}$

desc: Objective function by cie
unit: [MECU]

$TOTobj_{year}$

desc: Total objective function
unit: [MECU]

3.3. The Constraints

3.3.1. Commercial Gas balance:

This constraint is used to garanty the gas balance, for each node and for each commercial flow. A commercial flow is characterised by two companies: the selling company and the purchasing one. Gas input in a node may be the consequence of a gas extraction, a gas importation or a gas transit. In the latest case, the same amount of gas will appear as an output.

Gas output are the consequence of gas consumption, gas exportation and gas transit.

The constraint, called $GASbalance_{cie,ciebis,node,an}$, , where cie defined the company that sells the gas and ciebis, the purchasing company, may be described as [BCM/YEAR]:

For every node and every commercial flow:

Production supplied by extraction company
+ Net importation from existing long term contracts
+ Net importation from new short term contracts

MUST BE GREATER OR EQUAL TO

transit losses in pipelines
+ indogeneous demand at node

- in GAMS and with more details:

Production located at this node supplied by the selling company (cie) to purchasing company (ciebis):

$$EXTRACTION_{cie,ciebis,node,an}$$

Importation, exportation or transit of gas through new short term contracts:

$$\sum_{PIPE\$LINKnARR_{node,pipe}} FLOW\_FORW_{cie,ciebis,pipe,an} - FLOW\_BACK_{cie,ciebis,pipe,an}$$

$$- \sum_{PIPE\$LINKnDEP_{node,pipe}} FLOW\_FORW_{cie,ciebis,pipe,an} - FLOW\_BACK_{cie,ciebis,pipe,an}$$

Importation, exportation or transit of gas through existing long term contracts:
(this term is not a variable, existing contracts are exogenous)

$$\sum_{PIPE,CONTRACT \left| \begin{array}{l} LINKnARR_{node,pipe} \texttt{ i.e. arriving pipeline} \\ ECtoPIPE_{contract,pipe} \texttt{ = -1 in the backward sense,+1 in the forward} \\ CtoSELcie_{contract,cie} \texttt{ i.e. } cie \texttt{ is the selling company} \\ CtoBUYcie_{contract,ciebis} \texttt{ i.e. } ciebis \texttt{ is the purchasing company} \end{array} \right.} ECtoPIPE_{contract,pipe} * ECamount_{contract,an}$$

$$- \sum_{PIPE,CONTRACT \left| \begin{array}{l} LINKnDEP_{node,pipe} \texttt{ i.e. leaving pipeline} \\ ECtoPIPE_{contract,pipe} \texttt{ = -1 in the backward sense,+1 in the forward} \\ CtoSELcie_{contract,cie} \texttt{ i.e. } cie \texttt{ is the selling company} \\ CtoBUYcie_{contract,ciebis} \texttt{ i.e. } ciebis \texttt{ is the purchasing company} \end{array} \right.} ECtoPIPE_{contract,pipe} * ECamount_{contract,an}$$

$$\geq$$

Transit losses in pipeline
(rem.: in TEG, it is up to the transmission cie to fill up the losses appearing on their pipelines). This variable is defined in the PIPE_LOSS equation.

$$+LOSS_{cie,ciebis,node,an}$$

Demand located at this node for consumption nodes (by commercial contract):
The demand is disagregated into sectors. The variable CONSUMP represents the inflow of ciebis to the demand sector (the cie terms reminds the origin of the gas).

$$+ \sum_{COUNTRY,SECTOR \,|\, NODEtoCC_{node,country} \texttt{ i.e. this node belongs to the country}} \mathrm{CONSUMP}_{\texttt{cie,ciebis,country,sector,an}}$$

3.3.2. Transformation of commercial flows into a physical flow

In order to compute the losses in pipelines, one must know the actual flow (physical flow). The purpose of this constraint is thus to transform the commercial flows into the actual one.

The constraint, called $\mathrm{TRANSF}_{\mathrm{pipe,nodean}}$, may be described as [BCM/YEAR]:

For every pipeline:

The sum of all commercial flows (backwards + forwards)

MUST BE EQUAL TO

A unique flow in the forward xor backward direction

- in GAMS and with more details:

$$\sum_{cie,ciebis} FLOW\_FORW_{cie,ciebis,pipe,an} - FLOW\_BACK_{cie,ciebis,pipe,an}$$

$$+ \sum_{CONTRACT|ECtoPIPE_{contract,pipe}} ECtoPIPE_{contract,pipe} * ECamount_{contract,an}$$

$$=$$

In order to minimise to losses in the nodes, only one of QAF or QAB will not be null.

$$QAF_{pipe,an} - QAB_{pipe,an}$$

3.3.3. Computation of the gas losses

Thanks to the preceding constraint, one are now able to compute the gas losses in a node. Those losses must be filled up by the company owning the pipeline arriving at node.

The constraint, called $\text{PIPE\_LOSS}_{\text{node,cie,an}}$, may be described as [BCM/YEAR]:

At every node and for every company:

The losses incumbent on a company

MUST BE PROPORTIONAL TO

The physical flow in the pipeline arriving at that node * ratio of that pipeline owned by the company.

- in GAMS and with more details:

$$\sum_{CIEbis} LOSS_{ciebis,cie,node,an}$$

$$=$$

$$\sum_{PIPE \left| \substack{LINKnARR_{node,pipe} \\ PIPEown_{pipe,cie}} \right.} \left(QAF_{pipe,an} - QAB_{pipe,an}\right) * \left(1 - TRANSdesc_{pipe,'eff'}\right) * PIPEown_{pipe,cie}$$

3.3.4. Representation of the security of supply constraint

This constraint says that a country must have different source of supply in order to provide against supply outage.

The constraint, called $\text{SECURITY}_{\text{cie,country,an}}$, may be described as [BCM/YEAR]:

For every company providing gas to customers of a country:

The amount of gas provided by a gas producer to a country

CANNOT BE GREATER THAN A CERTAIN RATE OF

the total amount of gas consummed in that country.

- in GAMS and with more details:

$$\sum_{CIEbis,SECTOR} CONSUMP_{cie,ciebis,country,sec\,tor,an}$$

$$\geq$$

$$SECU\_RATE_{country,cie} * \sum_{CIEbis,CIEter\,sec\,tor} CONSUMP_{ciebis,cieter,country,sec\,tor,an}$$

3.3.5. Extraction capacity

The extraction capacity is borned due to gas field capacity.

The constraint, called $EXTR\_CAPA_{node,cie,an}$, may be described as [BCM/YEAR]:

For every company owning gas field in a specified node:

The amount of gas supplied by the company

IS LIMITED BY

the extraction capacity of that company.

- in GAMS and with more details:

$$\sum_{ciebis} EXTRACTION_{cie,ciebis,node,an} \leq EXTRA\_CHAR_{node,'capa'}$$

3.3.6. Linearisation of the consumption of a demand sector of a country

In order to endogenise the gas consumption, one must linearise the demand function into a succession of segments.

The constraint, called $CONSlinea_{country,sector,an}$ may be described as [BCM/YEAR]:

- in GAMS:

$$\sum_{CIE,CIEbis,NODE} CONSUMP_{cie,ciebis,country,sec\,tor,an} = \sum_{lLINEA} SEGMENT_{country,sec\,tor,linea,an}$$

3.3.7. Objective function by company

We shall now detail the costs supported by each company, every year. The basic lines of those costs are:

- The extraction operating cost
- The purchase price of existing contract (cost or revenue)
- Transmission cost or revenue
- Transport cost or revenue
- Distribution cost or revenue

All those costs are aggregated in the variable CIEobjcie,an. We are now going to detail each of those costs (the equation shall be continued from paragraph to paragraph).

The extraction cost

$$\sum_{NODE,CIEbis} EXTRACTION_{cie,ciebis,node,an} * EXTRA\_CHAR_{node,'oc'}$$

Purchase price or revenue for existing contract

$$\sum_{CONTRACT \mid CtoBUYicie_{contract,cie} \text{ i.e. the } cie \text{ buys gas}} ECamount_{contract,an} * ECprice_{contract}$$

$$- \sum_{CONTRACT \mid CtoSELLcie_{contract,cie} \text{ i.e. the } cie \text{ sells gas}} ECamount_{contract,an} * ECprice_{contract}$$

Transmission cost and revenue

$$\sum_{CONTRACT,PIPE \mid \substack{CtoBUYcie_{contract,cie} \text{ i.e. the } cie \text{ buys gas} \\ ECtoPIPE_{contract,pipe}}} ECamount_{contract,an} * TRANSdesc_{pipe,'cost'}$$

$$+ \sum_{PIPE,CIEbis} \left(FLOW\_FORW_{ciebis,cie,pipe,an} + FLOW\_FORW_{ciebis,cie,pipe,an}\right) * TRANSdesc_{pipe,'cost'}$$

$$- \sum_{CONTRACT,PIPE \mid \substack{PIPEown_{pipe,cie} \text{ i.e. the } cie \text{ owns the pipeline} \\ ECtoPIPE_{contract,pipe}}} PIPEown_{pipe,cie} * ECamount_{contract,an} * TRANSdesc_{pipe,'cost'}$$

$$- \sum_{PIPE,CIEbis \mid PIPEown_{pipe,cie} \text{ i.e. the } cie \text{ owns the pipeline}} \left(FLOW\_FORW_{ciebis,cie,pipe,an} + FLOW\_FORW_{ciebis,cie,pipe,an}\right) * TRANSdesc_{pipe,'cost'} * PIPEown_{pipe,cie}$$

Transport cost and revenue

$$\sum_{CIEbis,COUNTRY,SECTOR} CONSUMP_{ciebis,cie,country,sector,an} * DISTRdesc_{country,'trans'}$$

$$- \sum_{CIEbis,COUNTRY,NODE,SECTOR \mid \substack{NODEtoCC_{node,country} \text{ i.e. the node belongs to the country} \\ NODEtoCIE_{node,cie} \text{ i.e. it is a revenue only if the node} \\ \text{belongs to the cie}}} DEMrep_{node,country} * CONSUMP_{ciebis,cie,country,sector,an} * DISTRdesc_{country,'trans'}$$

Distribution cost and revenue (only for indirect customers)

$$\sum_{CIEbis,COUNTRY,SECTOR} \left(CONSUMP_{ciebis,cie,country,'dm',an} + CONSUMP_{ciebis,cie,country,'dm',an}\right) * DISTRdesc_{country,'distri'}$$

$$- \sum_{CIEbis,COUNTRY,NODE,SECTOR \mid \substack{NODEtoCC_{node,country} \text{ i.e. the node belongs to the country} \\ NODEtoCIE_{node,cie} \text{ i.e. it is a revenue only if the node} \\ \text{belongs to the cie}}} \left(CONSUMP_{ciebis,cie,country,'dm',an} + CONSUMP_{ciebis,cie,country,'dm',an}\right) * DEMrep_{node,country} * DISTRdesc_{country,'distri'}$$

3.3.8. Global Objective Function

We can now finally compute the global objective function since, all we have to take into account has been described into CIEobj variable. The only thing we must not forget now is to take the actualisation into acount, so that the global objective function becomes:

$$
\begin{aligned}
TOTobj_{an} = {} & \sum_{cie} \frac{1}{\left(1 + ACTU_{cie}\right)^{t}} \cdot CIEobj_{cie,an} \\
- {} & \sum_{linea,country,\sec tor} SEGMENT_{country,\sec tor,linea,an} * PRICEVAL_{country,\sec tor,linea,an}
\end{aligned}
$$

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