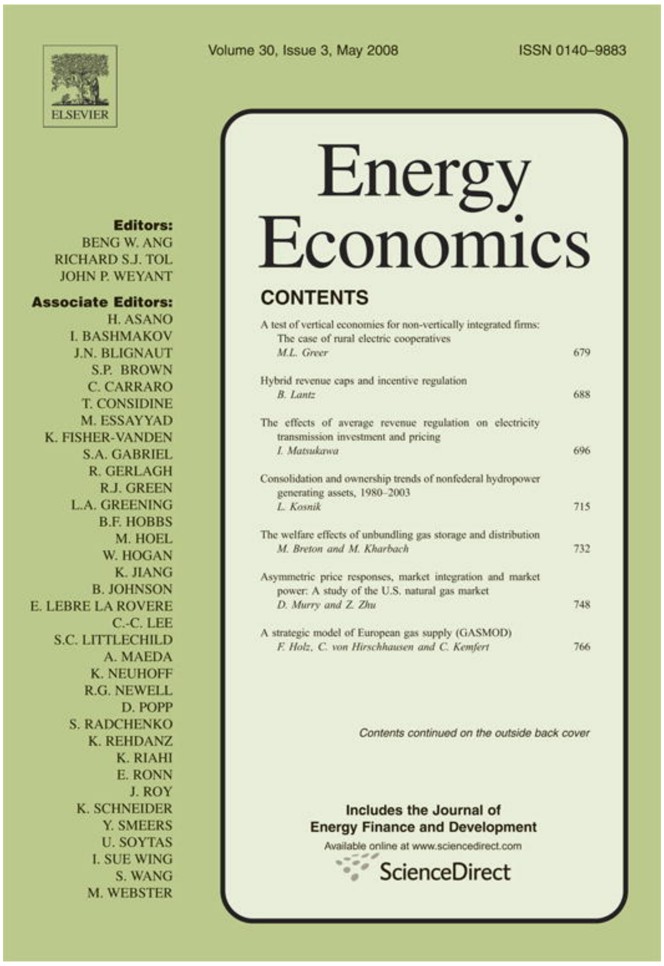
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A strategic model of European gas supply (GASMOD) ☆

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Abstract

This paper presents a model of the European natural gas supply, GASMOD, which is structured as a two-stage-game of successive natural gas exports to Europe (upstream market) and wholesale trade within Europe (downstream market) and which explicitly includes infrastructure capacities. We compare three possible market scenarios: Cournot competition in both markets, perfect competition in both markets, and perfect competition in the downstream with Cournot competition in the upstream market (EU liberalization). We find that Cournot competition in both markets is the most accurate representation of today's European natural gas market, where suppliers at both stages generate a mark-up at the expense of the final customer (double marginalization). Our results yield a diversified supply portfolio with newly emerging (LNG) exporters gaining market shares. Enforcing competition in the European downstream market would lead to lower prices and higher quantities by avoiding the welfare-reducing effects of double marginalization. Binding infrastructure capacity restrictions strongly influence the results, and we identify bottlenecks mainly for intra-European trade relations whereas transport capacity in the upstream market is globally sufficient in the Cournot scenario.

JEL classification: L13; L95; C61

Keywords: Natural gas; Strategic behavior; Non-linear optimization; Europe

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1. Introduction

The natural gas market in the European Union is undergoing considerable changes. Three main challenges for the next decades can be identified: the liberalization of the industry initiated by the European Union, the increasing demand for natural gas and, simultaneously, an increasing import dependency on gas supplied from outside the European Union. These factors have brought natural gas to the focus of the public's and politics' attention, and they underline that there is a need for better understanding the European gas market. The market structure within the European Union as well as the import relations to gas producing countries are issues that need further research. The numerical simulation model developed in this paper, called GASMOD, is a contribution to this research, taking a close look at demand and supply structures, and in particular at the infrastructure component. The static GASMOD model presented in this paper aims at combining a realistic representation of the market structure with an analysis of the limited infrastructure. The remainder of the paper is structured as follows: after a survey of the literature, we outline the structure of the European gas market, including the natural gas trade patterns. We then explain the data and the model structure. The subsequent simulation results are carried out in order to determine the "benchmark" model specification for the reference year. They are followed by the conclusions.

2. State of the literature

The GASMOD model follows a number of other modeling attempts of the European natural gas trade. The current structure of the trade relations suggests modeling the market with oligopolistic competition in a game theoretic framework. Mathiesen et al. (1987) are the first in the recent literature to study market power in the European natural gas market. They are followed by Golombek et al. (1995) and Golombek et al. (1998) who analyze the effects of liberalizing the natural gas market in Western Europe, distinguishing between upstream (producers) and downstream (traders) agents in the gas market. The numerical simulation of their model indicates that liberalization of the European gas market increases upstream competition and thus welfare. Golombek et al. (1995) have had a lasting influence on the further research in the field because they suggested marginal cost curves for several natural gas producers (Algeria, Russia/CIS, the Netherlands, Norway, and the United Kingdom) which have been widely used since.

However, analyzing oligopolistic energy markets with large-scale simulation models, in terms of data input, regional disaggregation, etc. is computationally challenging. For this reason there exist a number of linear programming models of the European, the North American or the global natural gas market. A drawback to this type of model is the underlying assumption of perfect competition. Generally, these models optimize social welfare which seems to be an unrealistic abstraction of a market where oligopolistic firms determine supply and prices. In the group of linear models and specifically for the European market, the EUGAS model (Perner and Seeliger, 2004) is a dynamic model of long-term optimization of European gas supply, taking into account production and transport capacities, but treating gas demand exogenously. Besides models of partial equilibrium, there also exist general equilibrium models with a high disaggregation for the gas sector. One example is the World Gas Trade Model (Hartley and Medlock, 2006). However, these models work with the underlying assumption of perfect competition as well, which makes them less appropriate for the studying the European market.

As highlighted by the first modeling attempts of the 1990s, the European natural gas market is characterized by an oligopolistic market structure with a small number of producers with access to

Europe, as well as a small number of wholesale traders in the European market. The NATGAS model (Zwart and Mulder, 2006) therefore chooses the representation of an oligopolistic producer market where a small number of strategic natural gas producers are facing price-taking arbitragers (traders) in the downstream market. A similar market setting is applied in Egging and Gabriel (2006) where the strategic producers bid with conjectured supply functions, as in several electricity market models.

Gabriel and Smeers (2006) provide a survey of strategic models for restructured natural gas markets, insisting on the fact that single stage models are generally easy to formulate, but that two stage models are more appropriate to capture the intricate reality of (European and other) natural gas markets; however, they are also more complex leading to possible avenues for future mathematical programming research. The GASTALE model (Boots et al., 2004) is the first attempt to apply the structure of successive oligopoly in gas production and trading in a large-scale simulation model. This model is similar to ours in that its underlying structure is a two-stage game. However, a number of simplifying assumptions, such as symmetry of traders, diminish the generality of this approach of double marginalization. Moreover, Boots et al. (2004) assume the domestic production to be an exogenous value instead of including it in the optimization. Another difference with GASMOD (see details in Section 3) is the use of cost functions and linear demand functions from Golombek et al. (1995). Whereas the static GASTALE model does not consider infrastructure capacity limitations, its recent dynamic version includes investments in scarce transport and production infrastructure (Lise et al., 2006a).

3. Structure and dynamics of the European natural gas sector

Both the demand side and the supply side of the European natural gas sector are currently undergoing substantial changes. These changes do not only have an impact on the natural gas market within Europe but also on the supply relations between Europe and other gas producing countries. Hence, the gas sector has been identified as a strategic sector by many institutions as the European Commission (European Commission, 2001) and the International Energy Agency (IEA). Let us briefly examine the three main challenges for the sector.

First, the European Union has pushed for a progressive liberalization of the European natural gas sector, a process that is still ongoing.[1] Ownership unbundling, third party access to gas transport infrastructure, and the end of the destination clause are some of the keywords in this process. With these efforts, continental Europe follows the United States and the United Kingdom. However, the liberalization process only slowly advances and the natural gas sector in many European countries is still characterized by *de facto* national monopolies of wholesale trading (e.g., Gaz de France in France, ENI in Italy, ENAGAS in Spain), or by a very limited number of active companies (e.g., E.ON-Ruhrgas, RWE, Wintershall, BEB in Germany) which leaves considerable space for strategic behavior to these companies.

Second, European demand of natural gas is rising and is expected to strongly increase further over the next decades. Natural gas will play an increasing role in the energy mix, mainly because of its relatively low carbon dioxide emissions in a context of growing climate concerns and political climate measures. The share of natural gas in the total primary energy demand in the European Union (EU-25) is expected to increase from 23% at present to a projected 32% in 2020.

[1] Cf. "Acceleration Directive" 2003/55/EC, which followed Directive 98/30/EC. Also see the results of the sector inquiry (European Commission, 2007).

This goes along with an increase of the absolute level of gas consumption from approximately 430 billion cubic meters (bcm) per year today to a projected 790 bcm/year in 2020 (IEA, 2004c). The rise in demand will mainly be driven by an increasing utilization for power generation; the share of natural gas in power generation is expected to rise from 15% in 2002 to over 35% in 2030 (IEA, 2004c, p. 154).

Third, Europe can only partly satisfy its gas demand with indigenous production, and therefore rising demand also implies increasing import dependency. Indigenous production in the European Union traditionally is concentrated in the United Kingdom and the Netherlands that account for three quarters of the European production.[2] However, production in these countries is decreasing because the fields in the North Sea are running out of gas.[3] The UK has already become a net importer of natural gas recently. In different scenarios, the gas import dependency of the EU-25 is estimated by the International Energy Agency to increase from the current 49% of supplies (233 bcm in 2002) to over 80% (639 bcm/year) by 2020.

A crucial question is where the future gas supplies will come from. Russia, the country with the largest gas reserves in the world[4], currently is the most important gas supplying country to the European Union (see Table 1) and is expected to expand this role. Its market share is projected to increase from the current 40% of EU imports to around two-thirds (European Commission, 2001). However, this forecast ignores the high investment costs that are needed to bring gas from new fields on stream, the large investments required to modernize and expand the transport infrastructure, and a certain political cautiousness in the EU not to rely too heavily on gas imports from Russia. North Africa, and especially Algeria, Egypt and Libya, have made significant efforts to improve their status as reliable, large-scale suppliers to Europe. Additional gas supplies will also come from new areas such as the Middle East, where 40% of the proven global gas reserves are located and where LNG export terminals have been constructed for about a decade now.

LNG is a form of supply with growing importance for Europe. It is part of the diversification efforts of many European countries. European LNG imports are currently bound by regasification capacity, but many regasification terminals are planned and constructed. LNG shipments mainly come from North Africa, Nigeria and the Middle East. The higher flexibility of LNG deliveries is one of the main differences with pipeline supplies which are bound by asset-specific infrastructure availability.

4. Data and model description

4.1. Data

We aim at an exhaustive representation of all relevant players on the European natural gas market.[5] This includes all countries within reach of pipelines as well as LNG exporters within economic reach of Europe (in the Atlantic basin and the Middle East). Table 2 summarizes the

[2] In our model, we do not consider Norway as a part of Europe since it is one of the big producers from outside the European Union. However, we do not define Europe exclusively as the European Union since we have included a number of non-EU gas importing countries such as Romania, Bulgaria, and Turkey.

[3] This is reflected by the reserves-production ratio, which was equal to 6.0 and 22.3 years at the end of 2005 for the UK and the Netherlands, respectively (BP, 2006).

[4] 47820 bcm, i.e., 26.6% of the proved global natural gas reserves (BP, 2006).

[5] Note that we concentrate on the trade relations, in a yearly perspective; hence, market stages such as storage which are relevant for inter-seasonal supply management are not included.

Table 1
Natural gas supplies to Europe from major exporters in billion cubic meters (bcm) per year (2004)

	Norway		Netherlands		Russia		Algeria		Middle East		Nigeria		Total imports
	bcm	%	bcm	%	bcm	%	bcm	%	bcm	%	bcm	%	
Belgium /Luxembourg	7	35%	8	37%	0	1%	3		–		–		21
Germany	26	29%	22	24%	38	41%	–		–		–		92
Finland/Sweden	–		–		5	81%	–		–		–		6
France	15	33%	–		12	26%	7	15%	0,1	0,2%	1	2%	45
Greece	–		–		2	80%	1	20%	–		–		3
UK	9	80%	1	4%	–		–		–		–		11
Italy	7	10%	10	14%	21	30%	26	37%	–		4	5%	70
Netherlands	4	32%			3	20%	–		–		–		14
Austria	1	10%	–		6	77%	–		–		–		8
Spain/Portugal	2	7%	–		–		16	53%	5	17%	6	20%	31
Baltic [a]	–		–		5	100%	–		–		–		5
Poland	1	5%	–		8	87%	–		–		–		9
Czech/Slovak Rep./Hungary	3	9%	–		24	85%	–		–		–		28
Former Yugoslavia	–		–		3	85%	0,4	11%	–		–		4
Bulgaria/Romania	–		–		8	85%	–		–		–		9
Turkey	–		–		14	65%	3	15%	–		1	5%	22
Total Exports to Europe	*75*		*40*		*146*		*56*		*5*		*12*		*378*

Source: BP (2005).

[a] Estonia from IEA (2004b) for 2003.

Table 2
Regions in the GASMOD model

Exporting regions	Importing regions
Algeria	United Kingdom
Libya	Netherlands
Egypt	Spain / Portugal
Iraq	France
Iran	Italy/Switzerland
Middle East (Qatar, UAE, Oman, Yemen)	Belgium/Luxembourg
Russia	Germany
Norway	Denmark
Netherlands	Sweden/Finland
United Kingdom	Austria
Nigeria	Poland
Trinidad	Czech Rep./Slovak Rep./Hungary
Venezuela	Former Yugoslavia/Albania
	Romania/Bulgaria
	Baltic States (Estonia, Latvia, Lithuania)
	Greece
	Turkey

exporting and importing regions included in the model.[6] We assume that there is one gas company per country or region, which is justified by current observations in several countries such as of GdF in France, Gazprom in Russia etc.[7]

We use data for the base year 2003. We focus on the trade relations so we do not distinguish intra-year seasons.[8] Data on reference trade flows, consumption and prices for the base year come from the International Energy Agency (IEA, 2004a,b) and from BP (2004). Data on production capacity in the European regions is based on IEA (2004b) and our own estimations. Transport capacity data comes from GTE[9], the European organization of the national TSOs (transmission system operators) for intra-European capacities, and from OME (2001) for exporter capacities. We use aggregated calibrated bilateral transport capacities for pairs of countries/regions, similar to Gabriel et al. (2005).

Production and transport cost data ("border prices") are taken from OME (2001). This is long-run marginal cost data, including likely investments on existing infrastructure. We add transport costs within Europe as costs per unit of gas and km of average distance between countries as assumed by Oostvoorn (2003); they include transport costs (e.g., gas used for compression), losses and possible transit fees. Given the long distance to the market, Russian gas is among the expensive suppliers in Europe. In the OME (2001) data, LNG is still a high-cost supplier with costs of around 3 US-$ per MMbtu (million British Thermal units) to the EU border for typical LNG exporters as

[6] We include Iraq and Venezuela although they have no gas export capacity yet because we want to be able to compute forecasts of their exports.

[7] This assumption is not uncommon in the literature, see for instance Egging and Gabriel (2006). However, the model formulation allows the inclusion of more than one player per country which would be more realistic when modeling the future European natural gas market.

[8] We are aware that omitting the seasonal pattern of natural gas trade leads to somewhat different results than using daily or seasonal data, especially with respect to capacity utilization. Indeed, one might find, e.g., a binding daily pipeline capacity in winter whereas the overall yearly capacity of that pipeline is not binding because of low utilization in summer. This effect is leveled in reality by the utilization of storage for inter-seasonal arbitrage.

[9] www.gte.be.

Table 3
Cost data (“border prices”) of selected producer countries

Producer country	Border price in US-$ per MMbtu	Border price in US-$ per thousand cubic meters (tcm)
Netherlands	1.65	52.15
Norway (to Germany)	2.10	82.06
Russia via Ukraine [a]	2.55	79.92
Algeria to Italy [b]/Spain [b]	2.07 / 2.15	84.41 / 85.63
Middle East (LNG) [b]	2.91	104.75

Source: OME (2001), and own calculations.
[a] Unweighted average border price at the Slovak border.
[b] Average border price weighted by export capacity.

Nigeria, Venezuela and the Middle East (Table 3). Norway is a producer at fairly high costs, whereas Algeria and the European producers (United Kingdom and the Netherlands) can export at relatively low costs to Europe. Political and other “soft” considerations (e.g., the reliability of an exporter) do not enter the cost data and are not taken into account in this model. The same is true for reserves which do not enter in the calculation of the production capacity of the producers.

4.2. Model

We structure the European natural gas market as a two-stage-game of successive imports to Europe (first stage, upstream) and trade within Europe (second stage, downstream). First, gas producing companies decide on their exports, mostly from countries outside Europe, to European countries. Simultaneously, domestic producers in Europe, for instance in Germany, Italy, Austria, etc. decide about their production quantities. Note that the endogenous determination of domestic production quantities is a novelty compared to previous models of the European natural gas market where domestic production usually is entered as an exogenous, pre-determined value. In the second stage, gas trading companies in Europe which have imported gas and which have bought domestically produced gas sell this gas in the European countries, including their own country.

We implicitly assume a liberalized, but oligopolistic market in Europe: TPA (Third Party Access) to the gas network is ensured for each exporter and each European trading company, and point-to-point pricing of transport is applied. There is no destination clause which means that consumers are free to choose their supplier which may well come from abroad (e.g., French consumers can purchase from the German trader). Since the focus of our model is on the strategic relations between the producers in the first stage, and between the traders in the second stage, we do not distinguish several market segments (such as industry, power generation, residential sector).[10] Furthermore, we implicitly assume that there is no vertical integration between the two stages. Even though one observes a tendency towards integration between producing countries (e.g., Russia) and wholesale traders (e.g., Wintershall) this is a reasonable assumption given the current market structure. We also consider the wholesale level and the consuming sector to be not integrated. Furthermore, we assume that there is one player per country.

GASMOD can be characterized as a game theoretic model assuming complete and perfect information. The producers in the first stage have perfect information about the demand situation

[10] This is a simplification because these different demand segments can exhibit varying demand patterns, e.g., with respect to their long-term contracting behavior, or the seasonal demand. However, as we consider yearly consumption and the long-term market drivers (thus neglecting the issue of long-term contracting vs. spot markets), it is also appropriate to take the total demand of all segments combined.

in the second stage and decide on their production quantities by taking into account the downstream market situation. According to standard game theory the appropriate method of determining equilibrium prices and quantities is backwards induction. At the equilibrium, the traders in the second stage are price-takers of the prices determined in the sub-game of the exporters in the first stage.

On each stage, the players play a non-cooperative game and maximize their individual payoffs. Following the literature of energy market modeling, we model the oligopolistic markets in both stages with Cournot (quantity) competition instead of Bertrand (price) competition.[11] By assuming an oligopolistic market structure in both stages the problem of double marginalization is represented: upstream and downstream markets are imperfectly competitive and suppliers in both markets exert market power, i.e., their price includes a margin. The downstream oligopoly leads to an additional price distortion and hence to an even less efficient allocation compared to the situation of a single oligopoly (cf. Spengler, 1950).

4.2.1. Upstream export market

The equilibrium in each stage is the solution of the non-cooperative game of the players given the demand for gas and certain capacity constraints. In each stage, each player maximizes his profits under capacity constraints. For the upstream exporter in the first market stage the constraints apply to the transport infrastructure: gas trade is restricted by the export infrastructure of each exporter f ($\mathrm{cap}_f^{\mathrm{exp}}$)and the capacity of each bilateral relation between an exporter f and a wholesale trader r ($\mathrm{cap}_{f,r}^{\mathrm{trade}}$).[12] Since we consider market relations we do not restrict bilateral trade relations to adjacent countries (as e.g., Egging and Gabriel, 2006). An exporter can supply each European region but not more than he can produce and ship out of his country/region (export capacity limitation) and than can physically be transported through the natural gas grid (or via the LNG terminals) connecting them (bilateral capacity restriction). Thus we can represent trade flows as observed in reality where for instance the Czech Republic imports natural gas from Norway (BP, 2006). The bilateral capacity limit of each trade relation (f,r) is computed given all possible ways to transmit natural gas from exporter f to wholesale trader r, and then calibrated such that each pipeline capacity is not exceeded although used by different trade relations. For the exporter f this gives us the following optimization program under (export and bilateral transport capacity) constraints:

$$
\begin{aligned}
&\max_{x_{f,r}} .\Pi(x_{f,r},p_r) = (p_r(X_r) - c_f(x_{f,r}) - tc_{f,r}(x_{f,r})) * x_{f,r} \\
&\text{s.t.} \sum_{r\in R} x_{f,r} \le \mathrm{cap}_f^{\mathrm{exp}} \\
&x_{f,r} \le \mathrm{cap}_{f,r}^{\mathrm{trade}} \\
&x_{f,r} \ge 0
\end{aligned}
\qquad (1)
$$

where $x_{f,r}$ is the supply by exporter f to wholesale trader r. $p_r(X_r)$ is the inverse demand function of each wholesale trader r with $X_r = \sum_{f\in F} x_{f,r} + x_r^{\mathrm{dom}}$. $c_r(x_{f,r})$ is the production cost function of

[11] Bertrand competition generally yields lower price margins and even prices equal to marginal cost (i.e., the perfect competition equilibrium) which would be unrealistic for a highly concentrated market as the natural gas market in Europe.

[12] We do not consider any restriction of production capacity or reserves because generally export capacity is below production of an exporter and the reserve situation does not matter in the static context modeled here.

producer f, and $tc_{f,r}(x_{f,r})$ is his transport cost function for delivering to trader r. We suppose unit production and transport costs, using OME (2001) data (see Section 4.1).[13] Transport costs within European countries are set as a constant value.

The Karush–Kuhn–Tucker (KKT) conditions of this optimization problem are sufficient for optimality because the (unit) cost functions of production, $c_f(x_{f,r})$ and transport, $tc_{f,r}(x_{f,r})$ are linear and the objective function to be maximized is convex, assuming that the inverse demand function $p_r(X_r)*x_{f,r}$ is concave, and the constraints are linear. The KKT conditions of the optimization problem of the exporter are:

$$0 \leq p_r(X_r) - \frac{\partial c_f(x_{f,r})}{\partial x_{f,r}} - \frac{\partial tc_{f,r}(x_{f,r})}{\partial x_{f,r}} + \frac{\partial p_r(X_r)}{\partial x_{f,r}} \cdot x_{f,r} - \lambda_f^{\text{exp}} - \lambda_{f,r}^{\text{trade}} \perp x_{f,r} \geq 0 \tag{2}$$

$$0 \leq \text{cap}_f^{\text{exp}} - \sum_{r \in R} x_{f,r} \perp \lambda_f^{\text{exp}} \geq 0 \tag{3}$$

$$0 \leq \text{cap}_{f,r}^{\text{trade}} - x_{f,r} \perp \lambda_{f,r}^{\text{trade}} \geq 0 \tag{4}$$

The Lagrangian multipliers λ_f^{exp} and $\lambda_{f,r}^{\text{trade}}$ of the capacity constraints are the shadow prices of these constraints and represent the value of an additional available unit of capacity.

Taking into account the behavioral assumptions of Cournot competition and the standard definitions of own-price elasticity and market share, we can simplify Eq. (2). In a pure Cournot–Nash equilibrium no player must have an incentive to move unilaterally; in other words the conjectured variation of the other players must be 0. Thus:

$$\frac{\partial X_r}{\partial x_{f,r}} = \alpha = 1 \tag{5}$$

We use this property (the parameter α) to define different model settings of either Cournot competition or perfect competition in one or both stages. Indeed, in the case of perfect competition each player is a price-taker in the market equilibrium, which gives:

$$\frac{\partial \left(\sum_{f \in F} x_{f,r} \right)}{\partial x_{f,r}} = \frac{\partial X_r}{\partial x_{f,r}} = \alpha = 0$$

Price elasticity σ_r in the market r, and market share $\theta_{f,r}$ of player f in the market r are defined by:

$$\sigma_r = \frac{\partial X_r}{\partial p_r} \cdot \frac{p_r}{X_r} \tag{6}$$

$$\theta_{f,r} = \frac{x_{f,r}}{X_r} \tag{7}$$

[13] Zwart and Mulder (2006) and Egging and Gabriel (2006) also assume unit production costs in order to ensure model traceability.

Taking the derivative of the production and transport cost functions gives the marginal costs:

$$\frac{\partial c_f(x_{f,r})}{\partial x_{f,r}} = mc_f \tag{8}$$

and

$$\frac{\partial tc_{f,r}(x_{f,r})}{\partial x_{f,r}} = t_{f,r} \tag{9}$$

Using definitions (5), (6), and (7) and Eqs. (8) and (9), we can simplify the KKT condition (2):

$$0 \leq p_r(X_r) - mc_f - t_{f,r} + \frac{\partial p_r(X_r)}{\partial x_{f,r}} \cdot \frac{\partial X_r}{\partial X_r} \cdot \frac{p_r(X_r)}{p_r(X_r)} \cdot \frac{X_r}{X_r} \cdot x_{f,r} - \lambda_f^{\text{exp}} - \lambda_{f,r}^{\text{trade}} \perp x_{f,r} \geq 0$$

$$mc_f + t_{f,r} \leq p_r(X_r) \cdot \left(1 + \alpha \cdot \frac{\theta_{f,r}}{\sigma_r}\right) - \lambda_f^{\text{exp}} - \lambda_{f,r}^{\text{trade}} \perp x_{f,r} \geq 0 \tag{10}$$

where $\frac{\theta_{f,r}}{\sigma_r}$ is the price margin obtained by the oligopolistic supplier. The margin is equal to zero in the case of perfect competition. With this formulation we follow Kemfert and Tol (2000) and Lise et al. (2006b) who use a similar optimization program in a model of the German respectively the European electricity market.

4.2.2. Domestic production

Just like the exporters, the domestic producers in Europe decide about their production quantities. Sales of the domestic producers are restricted to the wholesale traders r in the same country. Their optimization program is similar to the one of the exporters, as domestic producers optimize their profits under a restriction of production capacity.

$$\begin{aligned}
&\max_{x_r^{\text{dom}}} . \Pi(x_r^{\text{dom}}, p_r) = (p_r(X_r) - c_r^{\text{dom}}(x_r^{\text{dom}})) * x_r^{\text{dom}} \\
&\text{s.t.} \sum_{r \in R} x_r^{\text{dom}} \leq \text{cap}_r^{\text{dom}} \\
&x_r^{dom} \geq 0
\end{aligned} \tag{11}$$

We derive the KKT conditions which are sufficient for optimality of this problem because we assume unit costs, a concave demand function and we have a linear constraint. Using unit costs we can write the derivative of the production cost function as marginal costs:

$$\frac{\partial c_r^{\text{dom}}(x_r^{\text{dom}})}{\partial x_r^{\text{dom}}} = mc_r^{\text{dom}} \tag{12}$$

Using Eq. (12) and the definitions (5), (6), and (7), we obtain the following KKT conditions of the optimization problem of the domestic producer:

$$mc_r^{\text{dom}} \leq p_r(X_r) \cdot \left(1 + \alpha \cdot \frac{\theta_r^{\text{dom}}}{\sigma_r}\right) - \lambda_r^{\text{dom}} \perp x_r^{\text{dom}} \geq 0 \tag{13}$$

$$0 \leq \text{cap}_r^{\text{dom}} - \sum_{r \in R} x_r^{\text{dom}} \perp \lambda_r^{\text{dom}} \geq 0 \tag{14}$$

4.2.3. Downstream wholesale trade market

We proceed similarly for establishing the optimization program of the wholesale traders on the downstream market. Each wholesale trader is maximizing his profits that are determined by his revenues from sales to the final consumers minus the costs of purchasing and transporting gas, and given certain capacity constraints. The costs include the purchase of the gas at the local price p_r (at the location of the wholesale trader r) from the exporter, plus the transport costs from the trader r to the end-market m (intra-European transport costs $tc_{r,m}^{\mathrm{EU}}$). The supply by each trader r to each market m, $y_{r,m}$, is restricted by the intra-European transport capacity of the pipeline grid between him and each end- market m, $\mathrm{cap}_{r,m}^{\mathrm{EU}}$. Hence, the optimization problem of the wholesale trader r can be written as:

$$\begin{aligned}
&\max_{y_{r,m}} .\Pi(y_{r,m},p_m) = (p_m(Y_m) - p_r(X_r) - tc_{r,m}^{\mathrm{EU}}) * y_{r,m} \\
&\mathrm{s.t.}\, 0 \leq cap_{r,m}^{\mathrm{EU}} - y_{r,m} \\
&\, y_{r,m} \geq 0
\end{aligned} \tag{15}$$

where $Y_m = \sum_{m \in M} y_{r,m}$ and, $p_m(Y_m)$ is the local price of gas in each end market m. We again assume unit costs of transport which allows us to write the marginal transport costs as follows:

$$\frac{\partial tc_{r,m}^{\mathrm{EU}}(x_r^{\mathrm{dom}})}{\partial y_{r,m}} = t_{r,m}^{\mathrm{EU}} \tag{16}$$

$p_m(Y_m)$ is the inverse demand function of each end-market m faced by the wholesale trader. For the natural gas consumption in the end-market m, we chose a strictly decreasing, non-linear iso-elastic demand function of the form[14]:

$$Y_m = Y_m^0 \cdot \left[\frac{p_m(Y_m)}{p_m^0}\right]^{\sigma_m} \tag{17}$$

where Y_m and $p_m(Y_m)$ are the actual quantities and prices, Y_m^0 and p_m^0 are the reference demand and the reference price, respectively, in the market m in the base year, and σ_m is the price elasticity of the final demand. We prefer a non-linear to a linear demand function (as suggested by Golombek et al., 1995) because this allows for a non-negative demand for every price. We assume the demand elasticities σ_r and σ_m to be rather low in absolute terms (−0.7 for Western Europe, −0.6 for Eastern Europe)[15] which reflects a certain inelasticity of the natural gas demand.[16] Shifting from natural gas to another fuel would require changes in the technical installations, which are costly and time-demanding.

This demand function is inserted in the optimization problem of the wholesale trader since he is exerting market power and hence taking into account his influence on the demand function.

[14] The functional form of the demand function also draws from Kemfert and Tol (2000) and Lise et al. (2006b).

[15] We assume the price elasticity to be higher (in absolute values) by 0.05 for countries where natural gas does not have a large share in energy consumption, i.e., Spain/Portugal, Sweden/Finland, Poland, Balkan, and Greece. Thus we assume that switching to alternative fuels is easier for countries where dependency on natural gas is lower.

[16] Liu (2004) finds long-run own price elasticities for natural gas between −0.774 and 0.075 for OECD countries. Earlier estimations find higher elasticities (in absolute values), see e.g., Estrada and Fugleberg (1989), Al-Sahlawi (1989). Boots et al. (2004) use elasticities from Pindyck (1979) which are considerably higher (between 1.17 and 2.23).

Together with the marginal transport costs $t_{r,m}^{\mathrm{EU}}$, and the definitions (5), (6), and (7) this gives us the following KKT conditions for the wholesale trader:

$$p_r \leq p_m(Y_m) \cdot \left(1 + \alpha \cdot \frac{\theta_{r,m}}{\sigma_m}\right) - t_{r,m}^{\mathrm{EU}} - \lambda_{r,m}^{\mathrm{EU}} \perp y_{r,m} \geq 0$$

$$p_r \leq p_m^0 \cdot \left(\frac{Y_m}{Y_m^0}\right)^{\frac{1}{\sigma_m}} \cdot \left(1 + \alpha \cdot \frac{\theta_{r,m}}{\sigma_m}\right) - t_{r,m}^{\mathrm{EU}} - \lambda_{r,m}^{\mathrm{EU}} \perp y_m \geq 0 \tag{18}$$

$$0 \leq cap_{r,m}^{\mathrm{EU}} - y_{r,m} \quad \perp \lambda_{r,m}^{\mathrm{EU}} \geq 0 \tag{19}$$

4.2.4. Market equilibrium

Market clearing is reached at the intersection of demand and supply. We have a two-stage market: the demand coming from the downstream (end consumer) market, p_r, is addressed to the traders who forward it to the exporters. In other words, the two-stage game is solved by backwards induction by inserting Eq. (18), the solution of the optimization problem of the downstream trader, into Eq. (10), the solution of the upstream exporter. The market balance is given by equality (20) which must be verified for each market r:

$$\sum_m y_{r,m} = \sum_f x_{f,r} + x_r^{\mathrm{dom}}, \qquad \forall r \in R \tag{20}$$

The market balance together with the KKT conditions of each player (Eqs. (10), (3), and (4) of the exporter, Eqs. (13) and (14) of the domestic producer, and Eqs. (18) and (19) of the wholesale trader) give rise to the equilibrium model. Since there are equalities together with inequalities in this non-linear program, we have a mixed complementarity problem (MCP) model, which is programmed in GAMS, and solved with a standard algorithm for MCP, PATH.[17] The equilibrium solution is unique since we have a strictly decreasing demand function for each market and convex optimization problems with non-decreasing production functions resulting from constant (unit) costs.

5. Simulation results

The model is run for different market scenarios. We would like to assess which market scenario fits the current (2003) reality of the European natural gas market best. As discussed in the introduction, we assume that the European natural gas market is an imperfect market, with a double marginalization structure. To confirm this assumption we also simulate the scenarios of perfect competition in both markets or in the downstream market only. Whereas the scenario of perfect competition in both market stages seems unrealistic, the liberalization of the European gas sector is supposed to lead to a competitive downstream market in the future.

We recall that GASMOD is a quasi-static model to the extent that it only regards one time period. This means that we reproduce the base year 2003 and the results must be interpreted as market outcomes if the upstream and downstream markets corresponded perfectly to the characteristics of Cournot oligopoly or perfect competition. Thus, from the proximity of our results to the original data

[17] For more details about programming in the MCP format using the PATH solver see Rutherford (1995) and Ferris and Munson (2000).

we can derive conclusions about the actual market structure in the European natural gas market. In the following, we highlight the general results for the endogenous variables, thereby concluding about the currently prevailing market structure and effects of alternative market scenarios.

5.1. Upstream market: exports to Europe and domestic production

5.1.1. Exports

Table 4 reports the results for the exports in the first stage. Compared to the reference data for 2003 (also see Section 3, Table 1), in the *Cournot scenario*, exports from some traditional suppliers to Europe (Russia, Algeria) decrease while newly emerging exporters (Middle East, Nigeria) gain market shares. Among the large traditional exporters only Norway, the Netherlands and UK remain at a significant level. They have a comparative cost advantage both in terms of production as well as transport costs to the European markets, and can reach a relatively large number of traders in Europe. Most strikingly, Russia loses a considerable market share in Europe, partly because of its relatively high production and especially transport costs due to the long distance to the European market. This is also due to the model formulation of Cournot competition where large players like Russia have the same “strategic weight” as smaller players like Nigeria, Trinidad etc. Any buyer is interested in diversifying his supply portfolio in order to prevent a single exporter from exerting market power. For LNG we may expect an even greater increase of exports to Europe in the future since costs of LNG shipments are projected to decrease further in the coming years.

The comparison with the *perfect competition* scenario confirms that there is strategic withholding of quantities in the Cournot scenario in order to increase the price above marginal cost levels (also see Section 4.2.2. for the prices). In perfect competition, the higher demand because of lower prices

Table 4
Export quantities and market share (as percentage of total exports to Europe)

Exporter	Cournot competition		Perfect competition		EU liberalization		Reference exports to Europe 2003 [a]	Reference market share 2003
	Exports (bcm/year)	Market share	Exports (bcm/year)	Market share	Exports (bcm/year)	Market share		
Algeria	14.7	4.4%	66.0	14.6%	66.0	11.9%	57.0	17.6%
Libya	4.8	1.4%	14.5	3.2%	14.5	2.6%	0.8	0.2%
Egypt	5.0	1.5%	11.9	2.6%	11.9	2.2%	0	0.0%
Iran	0.0	0.0%	10.0	2.2%	10.0	1.8%	3.5	1.1%
Middle East	13.3	4.0%	26.6	5.9%	26.6	4.8%	2.4	0.7%
Russia	58.8	17.7%	196.0	43.3%	134.4	24.3%	131.8	40.1%
Norway	86.0	25.8%	86.0	19.0%	86.0	15.6%	68.4	20.8%
Netherlands [b]	66.6	20.0%	0.0	0.0%	80.4	14.6%	42.2	12.8%
UK [b]	59.4	17.8%	0.0	0.0%	81.5	14.7%	11.5	3.5%
Nigeria	12.6	3.8%	22.7	5.0%	22.7	4.1%	10.4	3.2%
Trinidad	12.0	3.6%	18.7	4.1%	18.7	3.4%	0	0.0%
Total	333.1	100.0%	452.4 [c]	100.0%	552.6 [c]	100.0%	328.7	100.0%

[a] *Source*: BP (2004).
[b] The Netherlands and UK are considered as exporters and as importers. In this table we have removed the exports to the traders in the Netherlands and UK. However, these quantities are available for re-export (including domestic consumption) in the 2nd stage.
[c] Excluding own domestic consumption in UK and the Netherlands. If domestic consumption is included, total “exports” are higher in the perfect competition than in the EU liberalization scenario as intuition suggests.

allows market entry and increased market share of higher cost producers such as Russia and Egypt, given that lower cost producers such as the UK, the Netherlands and Norway reach their capacity limits. LNG and other non-traditional exporters supply even more natural gas to Europe than in the Cournot scenario to satisfy the higher demand. The demand increase compared to the benchmark scenario is such that even higher cost producers are bound by their transport capacity (see Section 5.4.1). Since demand in the markets prefers the lowest-cost supplier, exporters first serve the markets which are closest to them (in terms of combined production and transport costs); in a context of high demand this explains why the UK and the Netherlands do not export to other European countries but supply only their domestic traders in the perfect competition scenario.

Finally, we see that a perfectly *competitive downstream market* (scenario "EU liberalization") would considerably change the outcome. Higher demand in the downstream market because of lower (competitive) prices triggers considerably higher exports. This contradicts the widespread thesis that an oligopolistic downstream market is the best response to an oligopolistic upstream market. Perfect competition in the downstream market with a given Cournot market on the export side also leads to more diversification of supplies.

5.1.2. Domestic production

Table 5 reports the quantities and market shares of domestic production. Domestic production is endogenously determined by the profit maximizing behavior of the producers. We observe that the higher demand due to lower prices in perfect competition and EU liberalization leads to domestic production being part of the supply portfolio in more countries than in the Cournot competition scenario. This completes the picture of a higher demand that needs to be satisfied under the perfect competition assumption. In both scenarios with perfect competition, domestic production is generally higher than observed in the reference data. Often domestic production serves the demand when trade capacities to a country are congested (see Section 5.4). This is especially true in the perfect competition scenarios where higher quantities would have been traded if physically possible.

5.2. Downstream market: intra-European wholesale market

5.2.1. Intra-European trade

Although the results of the first stage for the Cournot scenario may be somewhat surprising (e.g., the low Russian exports), the results of the second stage, and especially the final consumption, indicate a proximity to the real world situation. Indeed, as is shown in Table 6 we generally obtain results for this case that are close to actual final consumption in 2003. Clearly, this gives an indication to consider the Cournot case as the most realistic representation of today's European natural gas market. The consumption figures in the perfect competition and the EU liberalization scenario generally are higher than real world data. The notable exception of the UK can be explained by the prevailing competitive market structure in this country in contrast to continental Europe.

Looking at particular regions, some interesting features can be discovered (see Appendix, Table A1). For instance, direct exports to Germany (1st stage trade) only come from Northern Europe, especially Norway. This result is confirmed by sensitivity analyses with different price elasticities. However, Germany is still consuming Russian gas, as in reality, but which is indirectly supplied via Eastern European (Czech and Polish) and Austrian traders. Reciprocally, Russia is not directly exporting to Western Europe, but mainly to Eastern Europe. This is due to the production and transport cost structure. Hence, the results in GASMOD are driven by economic factors as opposed

Table 5
Domestic production quantities and market shares of the domestic producers in the upstream market

Domestic producer	Cournot competition		Perfect competition		EU liberalization		Domestic production 2003 in bcm (IEA, 2004b)
	Domestic production (bcm/year)	Part of the supply in the same country	Domestic production (bcm/year)	Part of the supply in the same country	Domestic production (bcm/year)	Part of the supply in the same country	
UK [a]	27.4	35.9%	120.0	100.0%	38.5	42.2%	108.4 [a]
Netherlands [a]	23.4	42.1%	90.0	80.7%	9.6	32.9%	73.1 [a]
Spain/Portugal			0.3	0.7%	0.3	0.7%	0.2
France			1.9	3.2%	1.9	2.9%	1.6
Italy/Switzerland			16.3	19.4%	16.3	13.4%	13.6
Belgium/ Luxembourg							0
Germany			13.2	21.5%	26.7	21.1%	22.2
Denmark	1.0	44.7%	8.5	100.0%	9.6	86.4%	8.0
Sweden/Finland							0
Austria							2.1
Poland	6.0	27.8%	6.8	38.3%	6.8	32.7%	5.6
CSH	3.9	14.7%	3.9	3.5%	3.9	15.3%	3.3
Balkan			4.1	100.0%	4.1	28.9%	3.4
Romania/Bulgaria			17.5	49.8%	17.5	69.3%	14.6
Baltic							0
Greece					0.03	0.9%	0.03
Turkey							0.6

[a] Here we report *exports* from the UK or the Netherlands to the trader in the same country.

to trade relations in today's reality that are often the consequence of geo-political considerations, the existence of destination clauses, and long-term contracts. However, the results of our model point to an increased diversity of supply which is also a political goal in Europe.

Table 6
Domestic consumption of natural gas in billion cubic meters (bcm) per year

Markets	Cournot competition	Perfect competition	EU liberalization	Consumption 2003
UK	49.5	113.3	95.9	95.4
Netherlands	38.9	69.6	56.9	40.3
Spain/Portugal	27.5	39.8	39.4	26.6
France	50.7	60.2	63.3	43.3
Italy/Switzerland	96.0	115.9	121.1	73.6
Belgium/Luxembourg	16.1	21.3	21.4	16.0
Germany	100.7	147.4	138.3	85.5
Denmark	0	6.2	5.7	5.4
Sweden/Finland	2.0	6.3	2.2	5.3
Austria	11.9	15.5	14.6	9.4
Poland	12.6	17.6	16.2	11.2
Czech/Slovak/Hungary	26.3	41.8	36.4	28.8
Balkan	9.7	10.0	10.5	7.7
Bulgaria/Romania	13.3	29.2	28.9	20.9
Baltic	0	3.3	5.7	5.0
Greece	2.3	3.7	3.6	2.3
Turkey	0	33.6	33.1	20.9
Total	457.6	734.7	693.4	497.6

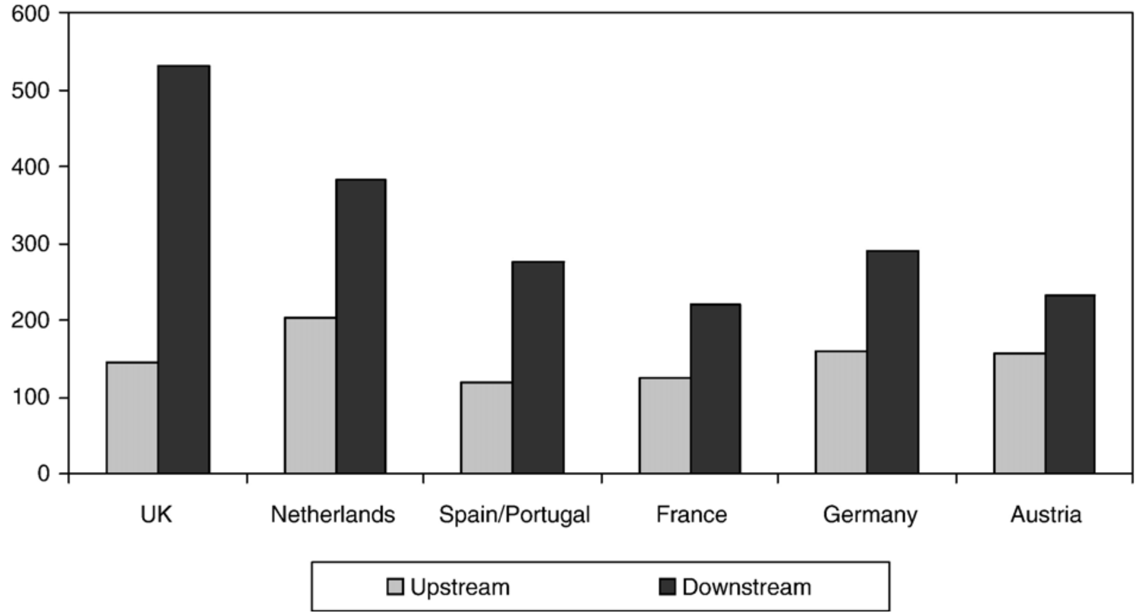

Fig. 1. Prices of selected countries (Cournot competition scenario) in US-$ per thousand cubic meters (tcm).

5.2.2. Prices

Figs. 1, 2 and 3 report the prices in the upstream market and the downstream market for some selected countries and for each simulation scenario. One clearly recognizes the effect of market power in the Cournot scenario (Fig. 1) where strategic withholding of production increases prices from one market stage to the next (double marginalization). When comparing Figs. 2 and 3, one also recognizes a large price increase of Cournot competition with respect to the market situations involving perfect competition in the other scenarios.

Prices are not only directly influenced by the market situation but also indirectly by the availability of import capacity for a market. Markets like the UK or Sweden/Finland for instance which benefit from the proximity to an exporter (own production or Russia, respectively) in the first stage cannot be supplied in the second stage due to missing infrastructure and therefore have to pay a high-mark-up to their local wholesale trader. This explains the heterogeneity of prices in the Cournot scenario, especially in the first stage. Clearly, this is a model effect which has to be removed for a more realistic representation of the European natural gas market, by modeling countries with this characteristic as competitive markets.[18]

There are two different aspects to consider in the scenarios with perfect competition (Fig. 2): prices are distributed homogenously between the countries, and prices generally are lower. For both scenarios, the premium added on the import price is equal to the transport costs of the marginal trader because there can be no oligopolistic margin added by the traders; often there is only intra-country trade so that the difference between prices in the upstream and the downstream market equals the assumed intra-country transport costs (2 US-$/tcm). Although exporters behave strategically in the EU liberalization scenario (Fig. 3) the prices are considerably lower than in the Cournot scenario and only about 20% higher than in the perfect competition scenarios. The double marginalization effect in the Cournot scenario visibly leads to higher endmarket prices than having an export oligopoly alone. This leads to the expectation that enforcing competition in

[18] For some traders, the first stage prices of the Cournot scenario are lower than the corresponding simulation results of the perfect competition or the EU liberalization scenario. This seems to be a modeling artifact due to the two-stage structure of the model. Indeed, for the endmarket prices we observe the expected relation of the prices of each scenario.

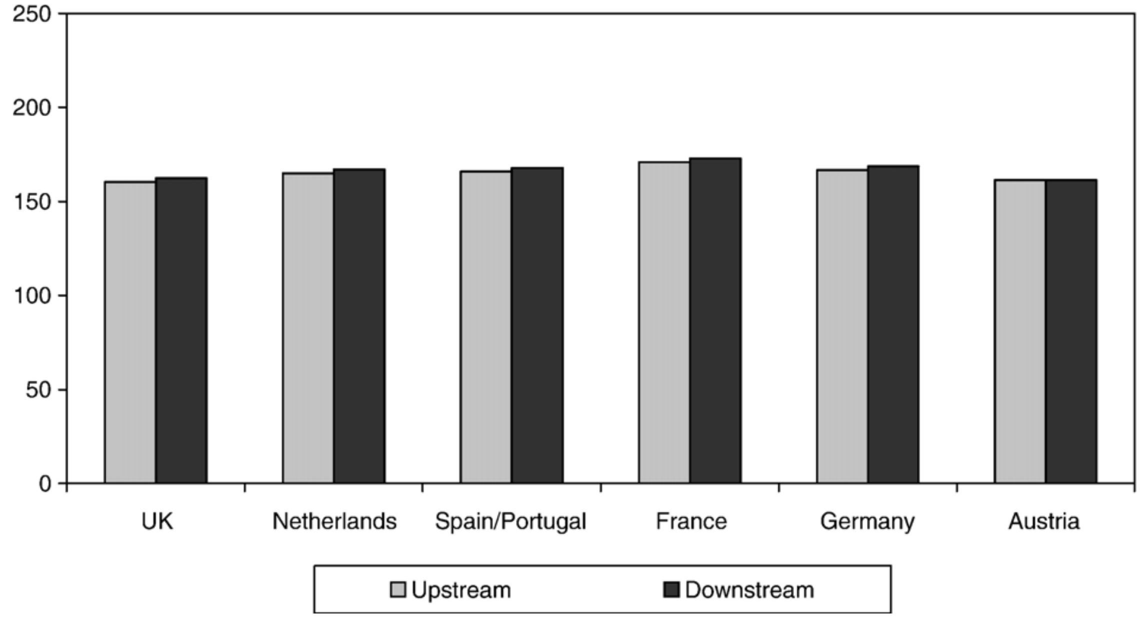

Fig. 2. Prices of selected countries (perfect competition scenario) in US-$ per thousand cubic meters (tcm).

the European market would lead to increased welfare because it allows higher consumption of natural gas combined with lower prices.

5.3. Welfare effects in Europe

As suggested by economic theory we find larger quantities and lower prices in the market scenarios with perfect competition compared to the Cournot scenario. This translates into higher welfare in Europe which has important implications for the market organization of the European natural gas sector, especially for the wholesale market. However, the traditional argument consists in rejecting the need to reduce the market power of only one of the market stages of a successive

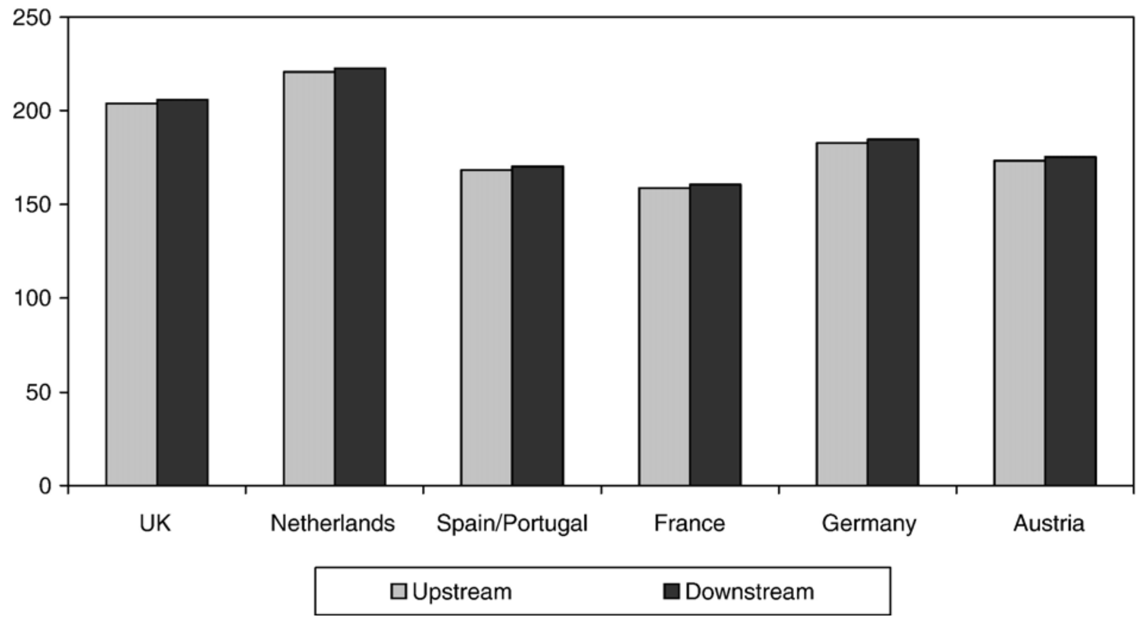

Fig. 3. Prices of selected countries (EU liberalization scenario) in US-$ per thousand cubic meters (tcm).

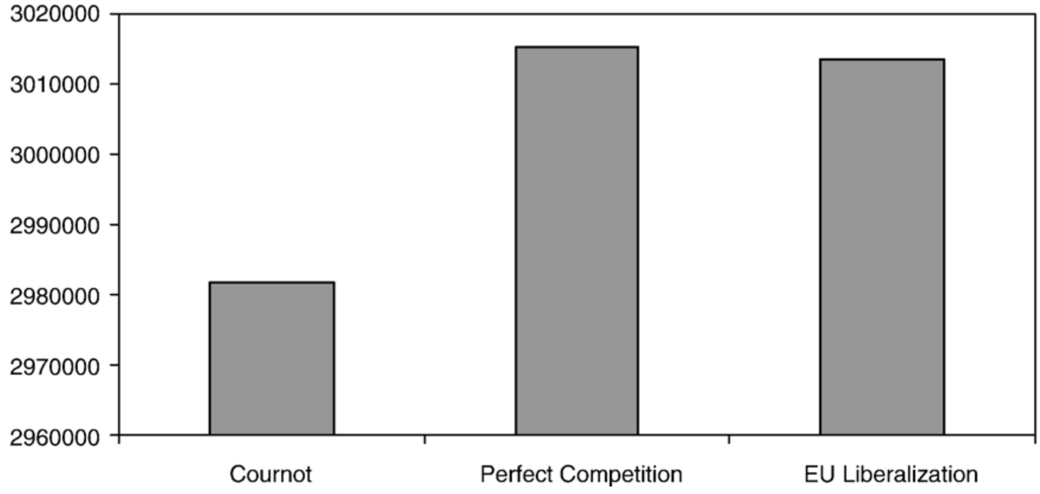

Fig. 4. Welfare results for all market scenarios, in US-$.

oligopoly because of the bargaining power effects of the other party. This argument is often brought forward by the European wholesale traders against regulation of their industry.

However, our findings differ from this argument. As depicted in Fig. 4, in the EU liberalization scenario we find a welfare close to the case of overall perfect competition. Both welfare results are unsurprisingly higher than in the double marginalization (Cournot) scenario. There are large welfare gains to expect from liberalizing the European wholesale market of natural gas. In contrast, the additional welfare gain from having a liberalized export market would be modest (about 0.06%) compared to the EU liberalization scenario, thus again making a case for enforcing competition in the European wholesale market.

5.4. Infrastructure capacity constraints

5.4.1. Upstream market

On the upstream market, the only transport route which is congested in the Cournot scenario is the Norwegian access to Europe. Norway has relatively modest production costs, and it is situated

Table 7
Export capacity utilization of each exporter

Exporters	Cournot competition	Perfect competition	EU liberalization
Algeria	22%	100%	100%
Libya	33%	100%	100%
Egypt	43%	100%	100%
Iran	0%	100%	100%
Middle East	50%	100%	100%
Russia	30%	100%	69%
Norway	100%	100%	100%
Netherlands	74%	0%	89%
UK	50%	0%	68%
Nigeria	55%	100%	100%
Trinidad	64%	100%	100%

Note that in addition to export capacity restrictions we have also introduced import capacity and bilateral trade restrictions. Whereas import capacity of European traders generally is not binding, bilateral trade capacity quite often is but with a structure similar to the export capacity utilization.

Table 8
Congested Intra-European capacity (used at 100%) in the Cournot competition scenario

From	To
Netherlands, Belgium, Germany	UK
UK, Germany, Belgium	Netherlands [a]
France	Spain/Portugal
Balkan (via Slovenia), France	Italy/Switzerland
Germany	Belgium/Luxembourg
Belgium, Austria [a]	Germany [a]
Germany	Poland
Austria	Czech/Slovak Republic/Hungary [a]
Italy/Switzerland	Balkan
Denmark [b]	Sweden/Finland [b]

[a] Note that these transport routes are also congested in the EU liberalization scenario.
[b] Only in the perfect competition and EU liberalization scenarios.

closely to high demand in North-West Europe, so that transport costs are modest, too; thus, Norway is well positioned as a supplier to Europe. Our results are reflected in reality by the stable reserve situation and the increasing production capacity in Norway which make it an important exporter for the coming decades with the need to expand its export infrastructure. Parts of these expansions, compared to 2003 data, are already under way with the opening of the Langeled pipeline to the UK in 2006.

In contrast, in the perfect competition case and very similar in the EU liberalization case, there are many exporters which are bound by their actual export capacities (Table 7), either pipelines or LNG liquefaction terminals, as of 2003. It is striking that even an exporter with large export capacities such as Russia reaches the bounds of its capacities but it gives an idea of the quantities that would be traded in a fully competitive market without capacity restrictions as compared to the actual natural gas market. This also shows the necessity to take into account infrastructure capacities when modeling a network industry such as the natural gas market.

5.4.2. Downstream market

In Table 8 we indicate the congested transport routes within Europe. We focus on the Cournot scenario as we have identified this as the most realistic representation of today's European natural gas market. The large number of bilateral transport routes that are listed seems surprising. But there clearly exist only a small number of cross-border natural gas pipelines within Europe, many of them with very limited capacity. Several studies have already pointed out that this is an important obstacle to the creation of a competitive Single European market of natural gas (European Commission, 2007; Neumann et al., 2006; Rupérez Micola and Bunn, 2007, for the specific link between the UK and the European continent).[19] Although we find a lot of congestion in two directions, this is not a necessary result since compressor capacity at a cross-border point may be such that more gas can flow in one direction than in the other. As discussed above, we observe in the results that missing

[19] The North American market experiences a similar situation with limited pipeline capacity separating the continental market into three regions with own price-setting mechanism (cf. Marmer et al., 2007).

transport capacity has a clear effect on prices since the local wholesale trader can possibly benefit from a quasi-monopoly.

6. Conclusions

In this paper, we have presented a model of the European natural gas market: GASMOD is a static model which structures the natural gas market as a two-stage game of successive i) exports to Europe, and ii) trade within Europe. In contrast to other models in the literature we apply a two-stage structure and incorporate an endogenous determination of domestic production. Infrastructure capacities which are an important characteristic of a network industry and which may be binding are explicitly taken into account in the model. We use GASMOD for numerical simulations with reference data for the base year 2003. We model three different market scenarios: Cournot competition in both (upstream and downstream) markets, perfect competition in both markets, and Cournot competition in the upstream market with a downstream market in perfect competition (EU liberalization).

We find that the scenario of Cournot competition is the most realistic representation of the current European natural gas market, with total export and final consumption quantities close to the reference data. However, our results present a more diversified picture of supplies to Europe, with newly emerging (LNG) exporters gaining market shares in Europe. This indicates that at present other factors are at play determining the supply relations in the real world (e.g., long-term contracts, destination clauses, etc.). With no surprise we find the highest prices, lowest quantities and lowest welfare in this scenario, thereby confirming the welfare-reducing effect of double marginalization. The results of several countries in the Cournot competition scenario are influenced by infrastructure capacity restrictions since a limited access to a market reduces the number of players which can then exert more market power.

Whereas the scenario of perfect competition is only simulated to benchmark the results of the Cournot scenario, the scenario of perfect competition in the downstream market in the presence of an oligopoly in the upstream market merits closer attention. Indeed this is a situation which could be enforced by the regulation authorities in Europe. We find that this case has an unambiguous welfare-enhancing effect compared to double marginalization. This contradicts the thesis that an oligopolistic downstream market is the best response to an oligopolistic upstream market. Our results also point to diversified supplies, which is another objective of European energy policy.

The comparison with real world data indicates that the current state of the European natural gas market is best represented by a scenario of Cournot competition. Deviations for some countries (e.g., the UK, Sweden/Finland) suggest that modeling their markets with competitive behavior might be more appropriate, be it in a competitive fringe for smaller exporters or traders, or as competitive market because of limited access to the market (which leads to unrealistically high mark-ups) or in the case of the UK because of its already successful market liberalization. There are several improvements which could be included in GASMOD, notably, the infrastructure bottlenecks that we have identified should be the basis for further investigation and for modeling the dynamics of the European natural gas market and of investments in its infrastructure. Another avenue for further research could be the inclusion of stochastic aspects, for example of demand, as in Zhuang and Gabriel (in press).

Appendix A

Table A1
Intra-European trade in the Cournot (double marginalization) scenario in billion cubic meters (bcm)

	UK	Netherlands	Spain/ Port	France	Italy/ Switzerland	Belgium/ Luxembourg	Germany	Denmark	Sweden/ Finland	Austria	Poland	CSH	Balkan	Romania/Bulgaria	Baltic	Greece	Turkey
UK	25.1	10.0	2.2	10.2	7.1	4.4	8.1			2.5	2.2	4.2	0.3				
Netherlands	8.3	12.7	2.2	1.4	2.0	2.0	20.4			0.7	1.8	4.2					
Spain/ Portugal			11.5										1.1				
France			2.2	15.4	7.1												
Italy/Switzerland					47.7								1.4				
Belgium/ Luxembourg	8.3	10.0	2.2	14.1	7.1	5.5	8.1			3.5	2.2	4.2	1.2				
Germany	1.6	1.6	2.2	8.1	7.1	1.6	31.1			2.3	2.2						
Denmark	1.6								0.6								
Sweden/Finland									1.4								
Austria	1.6	1.6	1.6	1.6	17.9	1.6	7.1			2.6	2.2	4.2	0.3				
Poland	1.6	1.6	1.2			0.2	11.8				1.1	4.2					
CSH	1.6	1.6	2.0			0.7	14.0			0.2	1.1	5.5					
Balkan					0.2								1.7	6.1			
Romania/Bulgaria													3.9	7.2		1.3	
Baltic																	
Greece																1.0	
Turkey																	
Total	49.5	38.9	27.5	50.7	96.0	16.1	100.7	0.0	2.0	11.9	12.6	26.3	9.7	13.3	0.0	2.3	0.0

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