GASMOD - Dynamic
- A Dynamic Model of the European Natural Gas Market and Network*

Submitted to the Annual Conference 2009 of the Verein für Socialpolitik

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March 1, 2009

Abstract

We develop a dynamic model of the European natural gas market and network that is based on the static GASMOD-Net model. GASMOD-Net includes the export and transit infrastructure of natural gas and its simultaneous use by several players within Europe in a simulation model of the European natural gas market. The dynamic extension focusses on endogeneous investments in the transport infrastructure (pipelines, LNG facilities) in an open-loop approach. Several players (producers, exporters, and wholesale traders) are active in the market(s) and their individual optimization problems together with the network constraints give rise to a complementarity model in the MCP format. We discuss more complex equilibrium concepts than the open-loop approach and its mathematical counterpart, the MCP model, and identify their limits for numerical simulations. Applying the GASMOD-Dynamic model to a small, stylized data set of the European natural gas market shows the importance of the transit infrastructure between European countries, in particular in an imperfect market.

1 Introduction

In this paper, we present a dynamic partial equilibrium model of the European natural gas market and network. While partial equilibrium models may not be able to accurately represent the interaction with other energy markets (e.g., the substition relation of natural gas and coal for power production), some aspects of the sector can be represented in more detail than in a general energy system model. In a so-called "network industry" as natural gas, it is specifically the infrastructure utilization that strongly influences the market outcomes and can be included in a partial equilibrium model. This paper focuses on the modeling of the network in an imperfect, spatially fragmented market and introduces investments into that network.

*I am indebted to Hannes Weigt, Florian Leuthold, Jan Abrell, Ruud Egging and Christian von Hirschhausen for their helpful comments and support.

Similar to earlier modeling efforts (e.g., Holz et al., 2008; Lise and Hobbs, 2008), we distinguish the following players active on international natural gas markets: producers and exporters on the upstream market, and wholesale traders on the downstream market. In addition, a network operator determines the network utilization and investments therein. We assume that all players are profit maximizers and that their optimization problems are subject to different constraints. In particular, the players have to respect network constraints which are introduced to describe the characteristics of the aggregated international transport system of natural gas into and within Europe. For each optimization problem, we derive the Karush-Kuhn-Tucker conditions which describe the optimality point under some assumptions and which together with the market clearing conditions give a complementarity model. This complementarity model is programmed in GAMS for simulations with a small data set describing the European natural gas market.

In the following, we first give an overview over the notation and the network graph. After describing the static network model, GASMOD-Net, we turn to the investment issue. We present the relevant concepts for investments in a game-theoretic complementarity model and we extend the static model to include investments in the network infrastructure (GASMOD-Dynamic). The paper closes with a small application of the GASMOD-Dynamic model and an outlook on further research.

2 Prerequisites

2.1 Notation

In this paper, and in particular in the subsequent model description, we use the following notation:

- A incidence matrix of the network
- a_n demand function parameter (intercept) in market n
- b_n demand function parameter (slope) in market n
- bp_n border price of exports arriving in importing node n
- C_n total consumption in consuming node n
- $cap^{(\cdot)}$ capacity constraint of different types (in superscript), such as production and pipeline capacity
- $CQ_{fn}\left(y_{fn}\right)$ production cost (function) of the
- δ_t yearly discount factor producer f in node n to produce quantity y_{fn}
- Exp exporter's problem (used as upper case index)
- f index of exporting producers
- i_{nm} investment in transport capacity on arc nm
- κ_{nm} multiplier of the investment capacity constraint for arc nm

- $\lambda^{(\cdot)}$ multiplier of different constraints such as production and pipeline capacity (type of constraint in superscript)
- m node, $m \in N$, with $m \neq n$
- N set of all nodes in the network
- n node, $n \in N$, with $n \neq m$
- $p^{(\cdot)}$ price (recipient in superscript) for each market (dual of respective market clearing condition)
- P producer's problem (used as upper case index)
- q_{fnm} exports of exporter f located in node n to import nodes m
- r index of wholesale companies
- $tfee_{nm}$ endogeneous transport fee to use an arc nm
- TOC_{nm} total costs pipeline operation of pipeline arc nm
- TFC_{nmt} total fixed (investment) costs in arc nm in time period t
- v_{fnm} export flows of exporter f between adjacent nodes n and m, including transit flows
- w_{rnm} wholesale flows of trader r between adjacent nodes n and m, including transit flows
- WS wholesaler's sales problem (used as upper case index)
- x_{rnm} wholesales of trader r located in node n to final market m with $m \neq n$
- y_{fn} production by producers f located in production node n
- z_{nm} total arc flow between adjacent nodes n and m

2.2 Network Description

Contrary to the representation of transport in Holz et al. (2008), we now include an explicit network that is used for transport between exporters and importers and at the same time between wholesalers and final consumer. In Holz et al. (2008), we used bilateral transport capacities between each pair of players. For each pair fr of exporters and importers and for each pair rm of wholesalers and final consumers we had individual capacity constraints cap_{fr}^{trade} and cap_{rm}^{EU}, respectively. In practice, this means that we implemented separate constraints between Russia and Germany, between Russia and Poland etc. We calibrated these constraints such that the obtained flows would not exceed the total available capacity on each link, even if this link is used by several pairs of players.

We assume each country of the European natural gas market to be one node in the network. Distances between the nodes are approximately the distance between the centers of the countries (in production countries with clearly defined natural gas production areas, these production areas will be taken instead of the geographic center of the country).

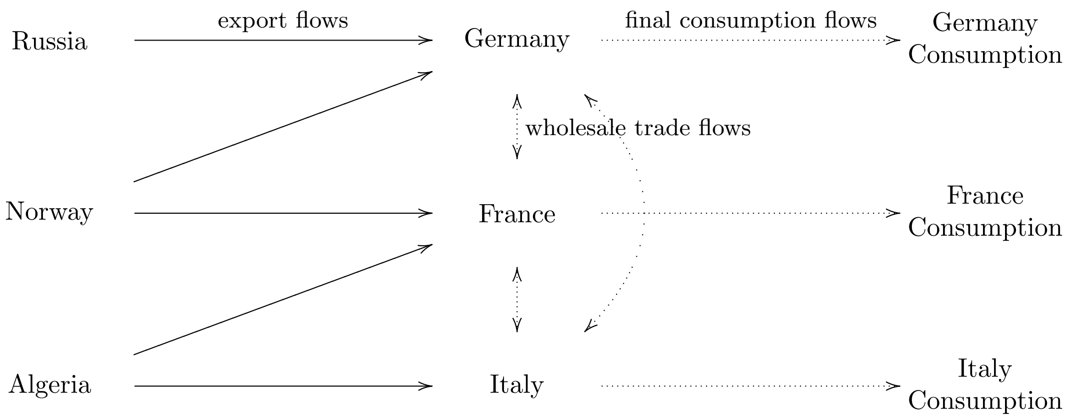

Figure 1: Graph of the 3-3-node example network

The following activities can take place in the nodes of the network: production, exports, imports/wholesales, and consumption. Each node may also be a transit node for a certain flow. Figure 1 shows a small exemplary graph of the European natural gas network. For clarity, we assume in Figure 1 that the activities take place in distinct nodes; in reality several activities can be located in the same node n.

Production is carried out in the production node (here: representing Norway, Russia, and Algeria). The produced natural gas is exported to the import nodes in Europe (here: Germany, France, Italy) along the solid lines. The exports can potentially transit via another European country before arriving at their final destination. For example, Russian exports to France will transit through the German node before arriving at the Italian node.

From their final destination node of import, the imported quantities are re-sold by the wholesale traders to the final consumption markets (nodes at the very right of Figure 1) along the dotted lines. The wholesale trader can sell to the final market of its own country or to the final market of the other European countries, potentially transiting through other countries. The two-stage structure of successive exports and wholesales is predetermined and exporters can not sell directly to the final consumer; this corresponds to the observed market structure in the European natural gas sector. The consumption node must be understood as a "virtual" node. It allows for non-zero wholesales from a wholesale trader located in a certain country to the final consumption market in the same country. The incidence matrix A of the 3-3-3 network in Figure 1 is:

$$A = \begin{pmatrix} 0 & 0 & 0 & \mathbf{1} & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & \mathbf{1} & \mathbf{1} & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & \mathbf{1} & \mathbf{1} & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & \mathbf{1} & \mathbf{1} & \mathbf{1} & 0 & 0 \\ 0 & 0 & 0 & \mathbf{1} & 0 & \mathbf{1} & 0 & \mathbf{1} & 0 \\ 0 & 0 & 0 & \mathbf{1} & \mathbf{1} & 0 & 0 & 0 & \mathbf{1} \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{pmatrix}$$

3 Optimization Problems of GASMOD-Net

In this section, we describe the static GASMOD-Net model. It is an extension of the static GASMOD model with path flows of natural gas. While the approach used in Holz et al. (2008) is no problem for a model with a small data set and a small number of external suppliers to an aggregated European importer (e.g., the GASTALE model), it is less appropriate for a detailed data set with a large number of (European) countries. Its caveat is to not take endogeneously into account the simultaneous use of a pipeline link by several players.

The inclusion of wholesalers in addition to exporters in our model makes the probability of simultaneous use of a link by several players even more likely. Moreover, the Cournot framework that we identified as a good description of the European natural gas market in Holz et al. (2008) leads to counterflows in the two directions of a pipeline arc because the Cournot outcome is not a least-cost solution of demand satisfaction. The model presented in this paper is able to account for these counterflows and the ensuing pipeline capacity need that is possibly higher than in a cost minimization model. Ccounterflows are a phenomenon that can be observed in reality as show the multiple cross-border points in Europe with pipeline and compressor capacity in two directions (GTE, 2008). We implemented a similar network representation in a single-stage setting in the European/World Gas Model (Egging et al., 2008a,b), where only one type of players, the exporters, uses the pipeline network.

Except for the wholesale trader, we assume all players to behave competitively. The perfect competitition assumption means that a player maximizes his profit until his marginal costs equal his marginal revenues (zero profit assumption). Hence, the profit maximization by competitive players is equivalent to welfare-optimal cost minimization. We make the assumption of competitive upstream players in order to avoid a possible multitude of equilibria. In the complementarity framework, this would give an MPEC or EPEC type of model if we want to solve the model globally and not only for a range of parameter values (as in the static GASMOD).[1] In this thesis, given the lack of general solution methods

[1] For this same reason, we concentrate on the export market in the EGM and WGM model and model the marketers only with the final demand function adressed to the exporting players (Egging et al., 2008a,b).

for EPECs, we choose a MCP formulation with competitive exporters here.[2] Our focus in this paper is rather on the integration of the network on a two-stage market setting.[3]

In the following, we detail the optimization problem of each type of player, with a particular focus on the elements related to the network model. From combining the KKTs of all players and the market clearing conditions we obtain a complementarity model, GASMOD-Net, that is extended in Section 4 to include investments in the network.

3.1 Producer

Each producer f is assumed to maximize his profit. His revenues come from the sales of total production y_{fn}, minus his production costs $CQ_{fn}(y_{fn})$. The production activity is subject to a capacity constraint for the entire country over the time horizon (here: one year). The producer sells to the subsequent player in the value-added chain, the exporter. We assume that production and exports are carried out within the same vertically integrated company f. Hence, producer and exporters do not behave strategically vis-à-vis each other and the price is determined by their market clearing condition (see below).

$$\begin{aligned} \max_{y_{fn}} \quad & \Pi^P_{fn} = y_{fnm} \cdot p^P_{fn} - CQ_{fn}\left(y_{fn}\right), \quad \forall f,n \\ \text{s.t.} \quad & cap^P_n \geq \sum_f y_{fn} \quad \left(\lambda^P_n\right), \quad \forall n \\ & y_{fn} \geq 0, \quad \forall f,n \end{aligned} \tag{1}$$

The profit maximization problem must be converted into a minimization problem to obtain the KKT conditions that will be part of the overall complementarity model. We have:

$$\begin{aligned} \min_{y_{fn}} \quad & - y_{fn} \cdot p^P_{fn} + CQ_{fn} \quad \left(y_{fn}\right), \quad \forall\ f,n \\ \text{s.t.} \quad & cap^P_n - \sum_f y_{fn} \geq 0 \quad \left(\lambda^P_n\right), \quad \forall n \\ & y_{fn} \geq 0, \quad \forall f,n \end{aligned} \tag{2}$$

The first-order conditions (FOCs) of this minimization problem give the Karush-Kuhn-Tucker conditions:

$$0 \leq -p^P_{fn} + \frac{\partial CQ_{fn}\left(y_{fn}\right)}{\partial y} + \lambda^P_n \quad \perp y_{fn} \geq 0, \quad \forall f,n \tag{3}$$

$$0 \leq cap^P_n - \sum_f y_{fn} \quad \perp \lambda^P_n \geq 0, \quad \forall n \tag{4}$$

These KKT conditions give the optimal point of the minimization problem if the problem is convex. Here, it depends on the shape of the total cost function $CQ_{fn}\left(y_{fn}\right)$.

[2] Formulating and solving the GASMOD-Net and the following GASMOD-Dynamic model as EPECs will be a topic for further research.

[3] It can be noted that the assumption of perfect competition leads to larger network needs (and, hence, investments) than in a Cournot model where quantities are strategically withheld.

Few data is available on the costs in the natural gas sector, but the literature generally suggests that the operating costs of production are characterized by a linear or a quadratic function (e.g., Golombek et al., 1995) which satisfies the convexity requirement.

Clearing between production and exports within the integrated company f located in node n is obtained if the total quantity produced (i.e. sold to the subsequent market stage, to the exporters) equals the total quantity purchased and sold by the exporter. We assume no losses in the export activity[4], and hence equality of purchases and sales of the exporter. There are two main reasons for the assumption of vertically integrated production and exports with separate optimization problems: i) a vertically integrated company corresponds to the observation in most countries and we therefore modeled a single player in the previous GASMOD model (Holz et al., 2008). However, producers and exporters have different revenue and cost structures and we prefer to distinguish them clearly.[5] ii) While distinguishing producers and exporters, one could model them as separate companies. This would necessitate more complex market clearing conditions between these two types of players and we deem it not necessary given the real-world observation of vertically integrated production and export activities.

$$y_{fn} = \sum_{m \neq n} q_{fnm} \qquad (p^P_{fn} \quad free), \quad \forall f, n \tag{5}$$

We want the equality in this market clearing condition to hold, i.e., the produced quantity should exactly equal the exported quantity. The dual variable of this equality is a free price, that is a price that can be negative, positive or zero. However, only a non-negative price would make sense from an economic point of view.[6] This must be ensured by the data input. Posing the market clearing condition as an inequality condition (which would enforce a non-negative price in the complementarity format) is the general case, but Aashtiani and Magnanti (1981) show that, under some monotonicity conditions, it can be guaranteed that the equality holds. Hence, the inequality constraint can be replaced by the equality condition, as used here.

3.2 Exporter

The exporter f maximizes his profit from selling quantity q_{fnm} to European countries $m \in N$ at border price bp_m. The costs of the exporter are the purchasing costs from the producer at price p_{fn} and the costs to transport the natural gas from the production node to the European import node in a series of arc flows v_{nm}. For using arc nm a price $tfee_{nm}$ has to be paid and hence the total transport costs for the exporters are $\sum_{nm} (tfee_{nm} \cdot v_{fnm})$.

We include a constraint ensuring the flow conservation for each node and activity of

[4]There are losses in the transport activity which we include in the total operating costs of transport, cf. Section 3.4.

[5]We use the same approach in Egging et al. (2008a).

[6]In electricity networks, negative nodal prices could be meaningful, too. This is because electricity flows are not only determined by the economic laws of supply and demand but also by the physical, so-called Kirchhoff's laws.

the player. For each activity of the exporter, market (trade) variables must equal all physical flow variables. Hence, considering node n as an "export node" of exporter f, all export sales out of node n ($\sum_{m\neq n} q_{fnm}$) must be equal to all export flows out of node n ($\sum_{m\neq n} v_{fnm}$): $\sum_{m\neq n} q_{fnm} - \sum_{m\neq n} v_{fnm} = 0$. Similarly, considering node n as an "import node", all import trade flows from all other nodes m ($\sum_{m\neq n} q_{fmn}$) must be equal to all physical import inflows ($\sum_{m\neq n} v_{fmn}$): $\sum_{m\neq n} q_{fmn} - \sum_{m\neq n} v_{fmn} = 0$. The same constraint must also hold for the transit nodes, i.e. nodes with no export or import sales activity (e.g., for sales of Russian natural gas to Germany, Belarus and Poland would be such transit nodes), where all inflows ($\sum_{m\neq n} v_{fmn}$) must equal all outflows ($\sum_{m\neq n} v_{fnm}$). Note that each node is at the same time in-node for some arcs (i.e. node "n" of arc (n, m)) and out-node for other arcs (i.e. node "m") which must be kept in mind for the derivation of the KKTs.

We have the following profit maximization program of the exporter, including the flow conservation constraint:

$$
\begin{aligned}
\max_{q_{fnm}, v_{fnm}} \quad & \Pi^{Exp}_{f,n,m} = q_{fnm} \cdot bp_m - \left(p^P_{fn} \cdot q_{fnm}\right) - \sum_{(nm)\in K^{Exp}_{f,n,m}} \left(tfee_{nm} \cdot v_{fnm}\right), \forall f, n, m \\
\text{s.t.} \quad & \left[\sum_{m\neq n} q_{fnm} - \sum_{m\neq n} v_{fnm}\right] + \left[\sum_{m\neq n} v_{fmn} - \sum_{m\neq n} q_{fmn}\right] = 0 \left(\phi^{Exp}_{fn}\right), \forall f, n \\
& q_{fnm} \geq 0, \quad \forall f, n, m \\
& v_{fnm} \geq 0, \quad \forall f, n, m
\end{aligned} \tag{6}
$$

The KKTs of the related minimization problem are:

$$0 \leq -bp_m + p^P_{fn} + \phi^{Exp}_{fn} - \phi^{Exp}_{fm} \quad \perp q_{f,n,m} \geq 0, \quad \forall f, n, m \tag{7}$$

$$0 \leq tfee_{nm} - \phi^{Exp}_{fn} + \phi^{Exp}_{fm} \quad \perp v_{f,n,m} \geq 0, \quad \forall f, n, m \tag{8}$$

$$0 = \left[\sum_{m\neq n} q_{fnm} - \sum_{m\neq n} v_{fnm}\right] + \left[\sum_{m\neq n} v_{fmn} - \sum_{m\neq n} q_{fmn}\right] \quad \left(\phi^{Exp}_{fn}\right), \quad \forall f, n \tag{9}$$

Given the assumption of competitive exporters, the "border price" of the importing country m, bp_m is determined by the market clearing with the subsequent market stage, that is with the importing wholesale trader r:

$$\sum_n \sum_f q_{fnm} = \sum_r \sum_n x_{rmn} \qquad (bp_m \quad free), \quad \forall n \in N \tag{10}$$

3.3 Wholesale Trader

Each wholesale trader r, located in a node $n \in N$, maximizes his profit from sales to a final market $m \neq n$. Node m may be the final market of a different country than the node of location of the wholesale trader n. The costs that the wholesale trader has to bear are the costs of purchasing the imports at the border price bp_n and the costs of transport of the flow w_{rnm} between his own node n and the final consumption node m.

A constraint similar to the exporter's problem will ensure flow conservation for each node and activity of the wholesale trader. More specifically, this constraint ensures that all contractual sales out of n and all physical flows out of n are equal: $\sum\limits_{m \neq n} x_{rnm} - \sum\limits_{m \neq n} w_{rnm} = 0$. Moreover, it must ensure that all wholesale imports in node m are equal to all physical inflows into node n: $\sum\limits_{m \neq n} w_{rmn} - \sum\limits_{m \neq n} x_{rmn} = 0$. Just as for exports, this flow conservation constraint must also hold true for a "transit node" of wholesales: $\sum_m w_{rnm} = \sum_m w_{rmn}$. Note that we assume for each country inside Europe (e.g., Germany, France) that it has at the same time a "transit node" within the European network and a final consumption node (see Figure 1). Although these are distinct nodes in the model graph, no costs of transport are assumed to occur for flows to a final consumption node because we abstract from domestic distribution costs and focus on the cross-border natural gas trade.

The wholesale trader's profit maximization program is:

$$
\begin{aligned}
\max_{x_{rnm}, w_{rnm}} \quad & \Pi^{WS}_{rnm} = x_{rnm} \cdot p^C_m(\cdot) - x_{rnm} \cdot bp_n - \sum_{nm} \left(tfee_{nm} \cdot w_{rnm} \right), \forall r, n, m \\
\text{s.t.} \quad & \left[\sum_{m \neq n} x_{rnm} - \sum_{m \neq n} w_{rnm} \right] + \left[\sum_{m \neq n} w_{rmn} - \sum_{m \neq n} x_{rmn} \right] = 0 \left(\phi^{WS}_{rn} \right), \forall r, n \\
& x_{rnm} \geq 0, \qquad \forall r, n, m \\
& w_{rnm} \geq 0, \qquad \forall r, n, m
\end{aligned} \tag{11}
$$

where $p^C_m(\cdot)$ is the final demand function that is taken into account by the oligopolistic wholesale trader. $p^C_m(\cdot)$ is replaced by p^C_m in case the wholesale trader is a price-taker. No physical constraints apply to the wholesale trader, given that the network constraints are taken into account by the network operator who passes them through via the price for arc utilization, $tfee_{nm}$. The KKT conditions of the related minimization problem of the wholesale trader are the following:

$$
0 \leq -p^C_m(\cdot) - \frac{\partial p^C_m(\cdot)}{\partial x_{rnm}} x_{rmn} + bp_n + \phi^{WS}_{rn} - \phi^{WS}_{rm} \quad \perp x_{rnm} \geq 0, \quad \forall r, m, n \tag{12}
$$

$$
0 \leq tfee_{nm} - \phi^{WS}_{rn} + \phi^{WS}_{rm} \quad \perp w_{rnm} \geq 0, \quad \forall r, m, n \tag{13}
$$

$$
0 = \left[\sum_{m \neq n} x_{rmn} - \sum_{m \neq n} w_{rnm} \right] + \left[\sum_{m \neq n} x_{rmn} - \sum_{m \neq n} w_{rmn} \right] \quad \left(\phi^{WS}_{rn} \quad \text{free} \right), \forall r, n \tag{14}
$$

where p^C_m is the market clearing price and $\frac{\partial p^C_m(\cdot)}{\partial x_{r,n,m}} = \frac{\partial p^C_m}{\partial x_{r,n,m}} = 0$ in case the wholesale trader is a price-taker and does not take into account the demand function. In case of a strategic wholesaler, the KKTs depend on the demand function. We assume the inverse demand function to be linear, and defined around a reference point $\left(C_n^{ref}, p_n^C\right)$. Total demand in consumption node n, C_{cn}, is emanating from the final consumers located in that country (combination of industry, power generation, and commercial/households). The linear inverse demand function is of the type:

$$p_n^C = a_n + b_n \cdot C_n, \qquad \forall n \tag{15}$$

where C_n is the total quantity demanded in node n, b_n the slope of the demand curve and a_n the intersection (prohibitive price). For the demand function, the following definitions hold true (here without indices for the nodes for the sake of easier reading):

$$\begin{aligned} C &= -\frac{a}{b} + \frac{1}{b} \cdot p, \quad \varepsilon = \frac{\delta C}{\delta p} \cdot \frac{p}{C} = \frac{1}{b} \cdot \frac{p}{C} \\ b &= \frac{p}{C} \cdot \frac{1}{\varepsilon}, \qquad a = p - b \cdot C \end{aligned} \tag{16}$$

Applying these to the reference point $\left(C_n^{ref}, p_n^C\right)$, we find the parameters a and b for the reference year and can specify the demand function parameters:

$$\begin{aligned} b &= \frac{p^{ref}}{C^{ref}} \cdot \frac{1}{\varepsilon} \\ a &= p^{ref} - b \cdot C^{ref} = p^{ref} - \frac{p^{ref}}{C^{ref}} \cdot \frac{1}{\varepsilon} \cdot C^{ref} \\ p &= p^{ref} - \frac{p^{ref}}{C^{ref}} \cdot \frac{1}{\varepsilon} \cdot C^{ref} + \frac{p^{ref}}{C^{ref}} \cdot \frac{1}{\varepsilon} \cdot C \\ &= p^{ref} + \frac{1}{\varepsilon} \cdot p^{ref} \cdot \left(\frac{C}{C^{ref}} - 1\right) \end{aligned} \tag{17}$$

Deriving the inverse demand function p_n^C with respect to x_{rmn}, we obtain:

$$\frac{\partial p_n \left(\sum_r x_{rmn}\right)}{\partial x_{rmn}} = \frac{1}{\varepsilon_n} \cdot \frac{p_n^{ref}}{C_n^{ref}} = b_n, \qquad \forall n \in N \tag{18}$$

which can be inserted in the KKT (12) of a strategic wholesale trader with market power.

We finally have the following market clearing condition for the final market. This market clearing is valid in any case, whether or not there is market power:

$$p_n^C - a_n + b_n \cdot \sum_{m \neq n} \sum_r x_{rmn} = 0 \qquad \left(p_n^C \quad free\right), \qquad \forall n \in N \tag{19}$$

3.4 Network Operation

The network is operated such that the available capacity on each arc nm is allocated according to the marginal willingness to pay for the transport by each player using the pipeline. The players that simultaneously use the network of pipeline and stylized LNG arcs are the exporters and the wholesalers. Their flows, v_{fnm} of the exporter, and w_{rnm} of the wholesaler, occur simultaneously on each arc (nm). The total flow on each network arc, z_{nm}, is hence defined as sum of all possible export and wholesale flows on that arc (nm). In the complementarity model, the following equation amounts to a market clearing condition between the network operator on the one hand and the exporters and the wholesalers on the other hand.

$$z_{nm} = \sum_f v_{fnm} + \sum_r w_{rnm} \quad (tfee_{nm} \quad \text{free}), \forall n, m \tag{20}$$

The coordination mechanism of network capacity allocation can be compared to a coordinated auction for transport capacity. The mechanism assigns the capacities (or fractions of the total available capacities) of the arcs to those players who have the highest marginal willingness to pay for it. We implement this with a network operator that is maximizing his profit where the revenue comes from congestion (and possibly other network) charges, minus the actual network operation costs. For a perfectly competitive profit maximizer, it can be interpreted as a benevolent (independent) transmission system operator whose objective is cost minimization (hence, welfare optimization). Indeed, as shown in Cremer et al. (2003), the profit optimization of the competitive network operator yields the same results as social welfare optimization, under the condition that the profit optimization problem is convex, so that the FOCs describe the optimal solution.

We assume the capacity to be known in advance (for each period) and to be given in units of natural gas per period (throughput). As explained in Bjorndal et al. (2007), who follow de Wolf and Smeers (2000), this is an approximation of the real-world dispatch problem of natural gas networks where pressure and other pipeline characteristics influence the available capacity on a pipeline link. However, Bjorndal et al. (2007) also argue that "for sufficiently constrained networks, the optimal solution" of the profit optimization of the network operator gives the same result as the optimization of social welfare. This is because the capacity constraint is the determining factor of the optimal solution in that case. It further supports our choice of a perfectly competitive network operator.

Assuming a competitive network operator, his profit optimization problem is:

$$\begin{aligned} \max_{z_{nm}} \quad & \Pi_{nm}^{Pipe} = tfee_{nm} \cdot z_{nm} - TC_{nm}(z_{nm}), \quad \forall n, m \\ \text{s.t.} \quad & cap_{nm}^{Pipe} \geq z_{nm}, \qquad \left(\lambda_{nm}^{Pipe}\right), \quad \forall n, m \\ & z_{nm} \geq 0, \qquad \forall n, m \end{aligned} \tag{21}$$

The KKT conditions of the related minimization problem are equivalent to the coordination mechanism described above:

$$0 \leq -tfee_{nm} + \frac{\partial TC_{nm}(z_{nm})}{\partial z_{nm}} + \lambda_{nm}^{Pipe} \quad \perp z_{nm} \geq 0, \quad \forall n, m \tag{22}$$

$$0 \leq cap_{nm}^{Pipe} - z_{nm} \quad \perp \lambda_{nm}^{Pipe} \geq 0, \quad \forall n, m \tag{23}$$

We assume the transport costs to be a linear function $TC_{nm}(z_{nm}) = a_{nm} \cdot z_{nm}$ where a_{nm} is distance-related, dependent on the mode of transport (onshore vs. offshore pipeline vs. LNG) and includes transport losses. A linear cost function ensures a convex problem of the network operator.

Equation (22) is equivalent to the standard definition of a transport price as the sum of marginal costs of delivering the transport service and the congestion price (shadow variable of an additional unit of capacity) along the arc nm. This standard definition of the transport price and the capacity constraint could also have been implemented "stand-alone" without refering to a ficticious player's optimization problem.

3.5 Complementarity Model

Collecting the KKTs of all optimization problems and the market clearing conditions gives a complementarity model. These are the KKTs (3) - (4) for the producer's problem, (7) - (9) for the exporter, (12) - (14) for the wholesale trader, (22) - (23) for the network operator and the market clearing conditions (5), (10), (19) and (20).

4 GASMOD-Dynamic

4.1 Modeling of Investments in Game Theory and the Complementarity Framework

This section shall serve for clarification of some concepts of investments in game theory and their equivalents in complementarity modeling. It will become apparent that the more realistic options to represent investments are computationally hard to solve and that a more "abstract" option to include investments is needed in an equilibrium model.

The investment decision is part of the overall game in the natural gas sector and its equilibrium may hence be influenced by the other market stages and vice versa (e.g., via transported quantities). We have a single, benevolent (competitive) "pipeline operator" to carry out the investment. There is, hence, no investment "game" strictly speaking (no strategic investment) as e.g. the investment games in electricity generation with several players that are investing.

Nevertheless, we have a multi-period, multi-stage game of operations and investment and it is therefore necessary to understand the different game-theoretical options. Two different equilibrium concepts are of importance for the modeling of a multi-period, multi-stage game:

- open-loop equilibrium
- closed-loop equilibrium[7]

    [a] pure closed loop equilibrium

[7] In the following we mean the equilibrium solution of a game in closed-loop (open-loop) strategies when talking about closed-loop (open-loop) equilibrium. The notions of game, strategy and equilibrium are used interchangeably.

[b] feedback equilibrium.

An open-loop equilibrium is described by Fudenberg and Levine (1988) as the solution of a game in which the "players need not consider how their opponents would react to deviations from the equilibrium path". In other words, the players of one market stage do not take into account the optimal solution of another market stage. In a multi-period game with perfect and complete information, this means that the decisions (investment, operations) of the future periods are taken at once in the initial period. In complementarity wording, an open-loop game can be solved as a mixed complementarity model with a standard solver.

For the closed-loop equilibrium, on the other hand, "all past play is common knowledge at the beginning of each stage"[period] (Fudenberg and Levine, 1988). In other words, each player takes into account the equilibrium solution of all other market stages when determining his optimal solution, and this in each period. Or, to put it differently, each player has to determine his reaction function to each possible strategy of all of his opponents. This gives potentially a very large strategy space, with a high chance of multiple equilibria. In game-theoretic terms, a closed-loop equilibrium must be a subgame perfect Nash equilibrium. In complementarity modeling, this amounts to either a mathematical or an equilibrium program under equilibrium constraints (MPEC or EPEC, respectively). While there are some solution algorithms for MPECs (optimization problem of a single player (e.g., pipeline operator) under equilibrium constraints), there is little chance today to numerically solve an EPEC (equilibrium problem of a market with several players under equilibrium constraints).

A subset of closed-loop games are so-called feedback games (Fudenberg and Tirole, 1991), a terminology that comes from control theory. Feedback strategies are only defined for variables which have a positive impact on the payoff function (i.e., are so-called Markovian strategies). The strategy set of closed-loop strategies may be larger than the one of feedback strategies because the former is based on all available past information (Fudenberg and Tirole, 1991). However, because feedback and closed-loop strategies coincide for most real-world applications, we use both concepts interchangeably.

For resource and natural gas markets, feedback equilibria are mentioned in Eswaran and Lewis (1985) and a follow-up survey paper by Flam and Zaccour (1989) who compare feedback (closed-loop) equilibria to open-loop equilibria, both analytically and numerically. In a dynamic game of resource extraction, Eswaran and Lewis (1985) show that both equilibrium concepts (open-loop and feedback) coincide analytically for certain functional forms.[8] They also show that for other functional specifications the results for both equilibrium concepts are rather close numerically. Flam and Zaccour (1989) give an even stronger conclusion, stating that for the European natural gas market of the 1980s - 2000s,

[8]For iso-elastic demand functions, the payoff/profit function in a period must not depend on the resource stock in that period, which is unrealistic because typically costs depend on the resource stock. For linear demand functions, all firms must be symetric in their resource stock which is also unrealistic for the world's resource markets.

open-loop and feedback equilibrium did coincide, essentially because the investments to be in place by 2000 were already decided in the starting period (1980s).

An open-loop strategy can be interpreted as a "precommitment" strategy given that the strategy is chosen at once at the beginning of the game and not updated, like in a long-term contract with fixed quantities.[9] Conversely, closed-loop equilibria are sometimes qualified as "credible" because they are sub-game perfect equilibria in each market stage and period (e.g., Flam and Zaccour, 1989). Eswaran and Lewis (1985) conclude that their work "lends some additional support to [...] precommitment equilibria in oligopolistic resource markets".

For the investment problem more specifically, Murphy and Smeers (2005) give a theoretical overview, with an application to investments in electricity generation capacity. They consider three types of models: a perfect competition model, an open-loop model which "extends the Cournot model" (and can hence be solved with a standard solver for Cournot games), and a closed-loop Cournot model that "separates the investment and sales decision" in a two-stage game (an EPEC, if more than one player decides on investments). They argue that the closed-loop game is the most realistic representation of reality and show that its solution falls between the open-loop and the competitive solution. This paper is only partially relevant for the investment problem in the network treated here, because it considers strategic generation investment by several Cournot players. Murphy and Smeers interpret the open-loop model as a situation where the quantity game is a long-term contract market not a spot market. This interpretation can also be realistic for the natural gas market where long-term contracts have long been prevailing, and where investment decisions have often been tied to long-term contracts due to the very high investment costs.

Lise and Kruseman (2008) for the electricity sector and Lise et al. (2005) for the natural gas transport infrastructure, propose a variation of the open-loop investment model which they call a recursive approach. In each period, the investment decision is taken based on an open-loop optimization of future profits of the upcoming period. The static market game in each period is run independently from (and in addition to) the investment game. The investment game updates the capacity constraint. A certain market structure must be assumed for each future profit optimization.

4.2 Investment in the Network: GASMOD-Dynamic

We now describe the functions that will modify the network and its capacities as used in Section 3.4. More specifically, the capacity constraint in the optimization program 21 is now endogeneous and obtained by a net present value optimization. We still consider a single, welfare-maximizing network operator. Hence, the investment is not strategic.[10]

[9] Eswaran and Lewis (1985) explain that precommitment strategies are unrealistic in cases like public resource ownership where the players do not have control and certitude over the time horizon. For this type of situation, closed-loop games are more realistic.

[10] For an example of a strategic game of pipeline investments, see Klaassen et al. (2004). They emphasize that such a game is characterized by multiple Nash equilibria.

As our focus is on the representation of investments in the network (incl. stylized LNG facilities), we exogeneously fix capacities of production (incl. capacity expansions or capacity reductions due to deteriorating reserve situation). Endogeneous production investment could, of course, be included in a later application. We use the one-shot open-loop optimization approach as in WGM (Egging et al., 2008b). Our ultimate goal is to implement a large-scale model. However, running multiple optimizations of a large-scale data set, as in a recursive approach, may be bound by computing capacity. In GASTALE (Lise and Hobbs, 2008; Lise et al., 2008), this is circumvented by reducing the data set size (especially the number of exporting and importing countries).

In terms of complementarity modeling, we formulate a MCP problem. Indeed, there is only one player (the network operator) who determines the optimal capacity simultaneously with the other players. This is contrary to a multi-stage decision where the network operator decides ahead of the other players (producers, traders). We assume perfect and complete information of all players about the other players' behavior. This means for example that the network operator knows the behavior of the exporters, wholesale traders etc. in the current and in future periods and can hence derive the optimal capacity.

The choice of the right investment incentive for the independent network operator is an important question. While we do not attempt to find the optimal regulatory policy, we still aim at a consistent representation of investments in the European natural gas sector. In the WGM model (Egging et al., 2008b), the revenue of the transmission system operator (TSO) is the future discounted congestion revenue from the new-built capacity. Similarly, in Hogan et al. (2007), the TSO earns his revenue from selling long-term financial transmission rights (LTFTRs) to potential capacity users/renters; the price for the LTFTRs is "related to the expected value of congestion revenues" from the incremental capacity.[11] It can be considered that the congestion price of an arc reflects the marginal willingness to pay of the using parties (exporters, wholesalers) for an additional unit of capacity. Having an independent network operator carrying out the investment is hence equivalent to having the producers and wholesalers as investors based on their expected payoff of an additional pipeline arc (additional capacity).

Leaving the investment decision with an independent network operator implies that neither producers nor European wholesale traders are active in the network expansion. This may seem as a simplification of reality where pipelines often are built and owned by individual production or trading players or by joint-ventures of several of these players. However, the European liberalization efforts have increasingly led to the unbundling and regulation of the natural gas transmission, with the aim of enforcing competitive pricing and behavior by the transmission system operators. While our results must be understood as a (normative) indication of where network investments would be welfare-optimal, they should coincide with the decisions in an effective regulatory regime.

[11] In Hogan et al. (2007) the transmission system operator also receives a fixed access fee from each network user, in addition to the LTFTR revenue. This fixed fee may be necessary to cover the investment costs, although the situation is different in the natural gas sector than in electricity where, due to Kirchhoff's laws, some lines may be beneficial although they do not have a positive shadow price.

We include short-term operating costs of the transport infrastructure in the profit function of the network operator, as we did in the static model in equation 21. In contrast, in the WGM and Hogan et al. (2007), marginal operating costs are not included in the future profits. This is an abstraction from reality but the theoretical literature is unclear on this point.[12]

The open-loop optimization is based on computing the discounted (= present value) future profits resulting of the market games in the future periods $t+1$, $t+2$, $t+3$, etc. We assume discrete time periods, following the literature, for example with five-year-steps. The network system operator optimizes his discounted net profits from the congestion revenue (net of the investment costs). Since congestion arises from the network utilization by the market players given their sales and flows, these sales and flows must be computed for all periods in the NPV optimization horizon.

In the complementarity model, equations (3)-(4) for the producer, (7)-(9) for the exporter, (12)-(14) for the wholesale trader and the market clearing conditions (5), (10), (19) and (20) remain the same as above, except that they are multiplied with the discount factor δ_t the variables and parameters receive a time period index t. The optimization problem 21 of the static GASMOD-Net model is replaced by the following combined long-term and short-term optimization problem of the network operator:

$$\begin{aligned} \max_{z_{nmt}, i_{nmt}} \quad & NPV_{nm} = \delta_n \cdot \sum_t \left[tfee_{nmt} \cdot z_{nmt} - TPC_{nmt}\left(z_{nmt}\right) - TFC_{nmt}\left(i_{nmt}\right)\right], \forall n, m, t \\ \text{s.t.} \quad & cap_{nm}^{Pipe} + \sum_{t'<t} i_{nmt'} \geq z_{nmt} \quad \left(\lambda_{nmt}^{Pipe}\right), \quad \forall n, m, t \\ & cap_{nmt}^{Inv} \geq i_{nmt} \quad \left(\kappa_{nmt}\right), \quad \forall n, m, t \\ & z_{nmt} \geq 0, \quad \forall n, m, t \\ & i_{nmt} \geq 0, \quad \forall n, m, t \end{aligned} \tag{24}$$

The KKTs that must be added to the KKTs from Section 3.5 are:

$$0 \leq \delta_t \cdot \left(-tfees_{nmt} + \frac{\partial TPC(z_{nmt})}{\partial z_{nmt}} \right) + \lambda_{nmt}^{Pipe} \quad \perp z_{nmt} \geq 0, \quad \forall n, m, t \tag{25}$$

$$0 \leq \delta_t \cdot \frac{\partial TFC_{nmt}(i_{nmt})}{\partial i_{nmt}} - \sum_{t'>t} \lambda_{nmt'}^{Pipe} + \kappa_{nmt} \quad \perp i_{nmt} \geq 0, \quad \forall n, m, t \tag{26}$$

$$0 \leq cap_{nm}^{Pipe} + \sum_{t'<t} i_{nmt'} - z_{nmt} \quad \perp \lambda_{nmt}^{Pipe} \geq 0, \quad \forall n, m, t \tag{27}$$

$$0 \leq cap_{nmt}^{Inv} - i_{nmt} \quad \perp \kappa_{nmt} \geq 0, \quad \forall n, m, t \tag{28}$$

The arc capacity cap_{nm}^{Pipe} is augmented in each period by the investment decisions of the previous periods by the network operator. The investment mechanism is such that

[12] The related literature on natural gas infrastructure investment from the Toulouse School of Economics (Cremer and Laffont, 2002; Gasmi and Oviedo, 2007) deals only with regulated capacity expansions as a tool to mitigate local market power.

there is a positive capacity increase for arcs nm only with a positive sum of the future shadow prices on that arc (i.e., a congested arc). In order to detect whether a greenfield project would be realized, it is necessary to include this arc in the data set with zero capacity in the starting period. If then $\lambda^{Pipe}_{nmt} > 0$, a player would have liked to use this arc beyond its current capacity. This is an indication that a capacity extension may be profitable. However, there will only be a positive investment if the total revenues from congestion fees for that incremental capacity exceed the total fixed costs $\sum_t TFC_{nmt}$.

Equation 26 shows that there is investment as long as the costs of investing an additional unit (marginal fixed costs) are covered by the network operators congestion revenue (and a possible shadow price of limited investment capacity). This is the usual zero-profit solution in perfect competition. The assumption of competitive behavior by the network operator ensures that he has no incentive to strategically increase congestion in order to increase its revenues by withholding capacity.

The exact capacity increase is decided endogeneously and it is assumed to be continuous and capped by an investment limit for each arc in each time period. The assumption of continuous investment is certainly a simplification, but can be taken in natural gas transmission where the increase of compressor capacity allows for the increase of transport capacities by small amounts. It is a common assumption in the literature, e.g. Lise et al. (2005); Perner and Seeliger (2004) because including an integer decision [yes-no] for an arc construction/extension introduces non-linearities to the model that may result in the impossibility to find an optimal result.

4.3 Application to a Small European Network

We use the small example network shown in Figure 1 in Section 2.2. The exporting countries are Russia, Norway, and Algeria, that are the largest exporters to Europe. As importing countries we include Germany, France, and Italy, traditionally the largest natural gas consumers in Europe. In this small application, we model three time periods in 10-year intervals: 2005 (original data), 2015 and 2025.

4.3.1 Data

The focus of this application lies on the network representation. We include the existing pipeline capacities[13] as of 2008 (GTE, 2008).[14] Column 1 in Table 3 in the subsequent section shows the included capacites. We allow for expansion of all existing arcs and for investment in an additional arc between Russia and Italy.[15]

We use linear costs of transport (unit marginal costs). These costs are higher for

[13] We also include the LNG capacities based on past flows between Algeria as exporter, and France and Italy as importers, as stylized arcs.

[14] Overall, there has been little change between the 2005 and the 2008 data, but some cross-border capacities were expanded. Given the tight intra-European capacities, we wanted to include the largest capacities available, hence the 2008 capacity data.

[15] This can be thought of as a stylized arc of the Trans-Austria pipeline that transports Russian gas via Ukraine and the Czech Republic to Austria, which we include with zero capacity in 2005

longer and offshore pipelines and for stylized LNG arcs. In the absence of reliable data on investment costs, we assume the investment costs to be a multiple of the short-term transport costs.[16] This is reasonable because both, short-term and long-term costs depend on the pipeline length, and are higher for offshore pipelines and for LNG terminals.

For production, and more precisely production available for exports, in Russia, Norway, and Algeria, we use own estimates of future production capacities and costs (Table 1). We assume production capacities in Norway and Algeria to remain stable and not to increase considerably, due to the Norwegian resource utilization policy and the uncertainty on available resources in Algeria. On the contrary, we increase the production capacity available for exports in Russia in the next decades, assuming that Russia will be able to tap new fields to substitute for the depleting existing fields, and to reduce its domestic energy and natural gas demand (with energy efficiency and possibly fuel switching measures). The increase in potential export capacity from Russia combined with the possibility to construct a pipeline link between Russia and Italy may lead to "greenfield" investment in the model.

However, the larger Russian production capacities come from expensive fields around and in the Arctic Sea (e.g., Shtokman, Yamal). Hence, we schedule the Russian costs of production to considerably increase, too. On the other hand, production costs in Norway and Algeria can be expected to increase only slightly due to the well-controlled technology (in Norway) and the rather favorable production conditions (in Algeria).

	2005		2015		2025	
	Production capacity	Production costs	Production capacity	Production costs	Production capacity	Production costs
Russia	180	70	200	90	250	120
Norway	100	65	120	70	130	75
Algeria	80	50	80	55	80	60

Table 1: Input data for production capacities (in bcm per year) and unit production costs (in US-Dollar per tcm)

We use 2005 demand data from IEA (2008) (industrial end-user prices) and BP (2008) (consumed quantities). We apply the growth rates published by EC (2008) and obtained with the PRIMES model to both, price and quantities. This means, we apply an annual growth rate of about 3% to the individual prices until 2015, and of about 1.5% between 2015 and 2025. For total consumption, the growth rates vary drastically between the three European countries. In particular, the data includes a reduction of natural gas consumption in Germany after 2015 and at the same time a strong rise in France and Italy. In the absence of available data on own-price elasticities, we use -1 for all years and countries. Reference prices and quantities and elasticity are used to construct demand functions for each year and country as described above in Section 3.3.

[16]In the last years, investment costs in natural gas transmission have been rather volatile. Since 2005, the natural gas sector saw a large cost increase (increase in prices of materials and engineering services) which was mainly due to high demand for investments. As this demand is likely to decrease in the coming years, hand in hand with economic recession and because the large number of current investment projects in the world may lead to some overcapacities, the investment costs may also decrease again.

We do not use a discount factor in this small model, but we keep in mind that the choice of the discount factor, relative to the investment costs, has an impact on the solution. The GAMS code in the Appendix includes the data as used and discussed here.

4.3.2 Results and sensitivity analysis

Table 2 shows the produced and consumed quantities for the model horizon. All producers keep their production stable (Algeria after an increase in the first period), below their maximum capacity. This suggests that they are bound by their export transport capacity but that this is not expanded. Consumption follows the same pattern as the input data for the demand functions, with a jump in consumption in France and Italy by 2025 and a drop in Germany.

	2005	2015	2025
Production			
Russia	128	150	150
Norway	65	65	65
Algeria	35	60	66
Consumption			
Germany	153	145	133
France	42	50	56
Italy	33	80	92

Table 2: Model results: production and consumption, in bcm per year

In Table 3 we report the arc capacities for each model period. The increased capacities are highlighted in bold font. There is no investment in 2025 (the last time period in this example) because any increased capacity would not be used. The very limited original capacities in the starting period lead to a strong investment in the first period. In several cases, this investment is carried out with 100% of the possible incremental capacity (from Algeria to Italy, and from Germany to Italy and France).

From	To	2005	2015	2025
Russia	Germany	150	150	150
Norway	Germany	45	45	45
Norway	France	20	20	20
Algeria	France	10	10	10
Algeria	Italy	25	**50**	**56**
Germany	France	14	**29**	**35**
Germany	Italy	6	**21**	**27**
France	Germany	2	2	2
France	Italy	2	**9**	9
Italy	France	1.5	1.5	1.5
Germany	Germany	500	500	500
France	France	500	500	500
Italy	Italy	500	500	500

Table 3: Network capacities in 2005 (original data), 2015 and 2025 (model results), in bcm per year

As could be expected from the observed production quantities, there is hardly any investment in the export pipelines, with the exception of the Algeria-Italy pipeline. This is because additional export flows could not be transported beyond the border country due to limited intra-European capacity. Again, that is why we obtain investments at the capacity limit for several pipelines between European countries. In particular, the pipelines from Germany to France and Italy that deliver Russian natural gas are expanded. Moreover, the pipeline between France and Italy receives additional capacity to satisfy the strong increase in Italian demand. Many other pipelines have positive shadow values for λ_{nmt}^{Pipe} as well (Table 4), but they are not large enough to cover the investment costs, and hence the investment is not carried out. In particular, the link between Russia and Italy is not built despite the high demand in Italy and the positive shadow value of this link.

From	To	2005	2015	2025
Russia	Germany		95.2	132.0
Russia	Italy	580.2	464.9	432.5
Norway	Germany	8.0	118.2	180.0
Norway	France	352.6	386.9	381.0
Algeria	France	366.6	400.9	395.0
Algeria	Italy	608.2	507.9	500.0
Germany	France	343.6	267.6	200.0
Germany	Italy	580.2	369.6	300.0
France	Italy	235.6	101.0	99.0
Italy	Germany		28.8	86.7

Table 4: Shadow values of arc utilization

Our model includes the downstream wholesale market in addition to the export flows to Europe. This is a major difference to previous models in the literature. Table 5 shows the final sales of the wholesale traders in 2025. The flows (and hence the sales) are not only determined by the interaction with the final demand but are also constrained by the infrastructure availability. Moreover, wholesalers and exporters are "competing" for the transport capacity in the European network and the player with the highest marginal willingness to pay is attributed the capacity. In our example, this results in no sales abroad by the Italian wholesaler while the French and in particular the German wholesaler reach out to their neighboring markets.

From/To	Germany	France	Italy
Germany	133	12	18
France		44	8
Italy			66

Table 5: Wholesales in 2025, in bcm per year

We carry out sensitivity analysis with changing the market power by the wholesale traders, but this does not modify the results. The reason for this is our assumption on market structure by the exporters in the MCP framework. The assumption of competitive exporters allows them to directly see the final demand (because it is directly passed on to them) and to satisfy it by selling to the local wholesale trader in the country where the demand is located. Unless they are restricted by lacking infrastructure, the exporters sell to the country where the final demand is located, using the intra-European network and leaving less capacity available to the wholesalers.[17]

A small application like the one presented in this section is particularly well-suited to perform some sensitivity analysis in order to better understand the drivers of the results. Table 6 shows the impact on the investment decision by a modification of the following parameters: reduction of the reference price by 50% (scenario called “demand”), increase of the investment costs by 100% (“costs”), and increase of the maximum allowed capacity in each period by a factor 10 (“capacities”).

		Base		Demand		Costs		Capacities	
From	To	2005	2015	2005	2015	2015	2025	2005	2015
Algeria	Italy	25	6.1	25		25		45	
Germany	France	15	5.9	15		15		18.4	
Germany	Italy	15	5.7	15		15		28.8	
France	Italy	6.9		1.1		1.2			

Table 6: Results of sensitivity runs on capacity expansion (in bcm per year of new-built transport capacity)

We reduce the reference prices because the data for 2005 was very high relative to earlier years, when comparable volumes where consumed. The high prices seem to be particularly relevant for Italy and France where the data reports higher prices and at the same time lower quantities than in Germany. Given that we use the same elasticity in all countries, the demand function is steeper in Italy and France. Indeed, flattening the demand functions overall has the effect to reduce the investments throughout the system and in particular after the first period.

The picture looks similar when doubling the investment costs. There are again no investments in the entire system after the first period. But the demand increase and the congestion within Europe are strong enough to justify high cost investments to France and in particular to Italy.

Lastly, allowing for ten times more capacity expansion than in the baseline run advances all investments to the first period. They are larger in magnitude than in the other scenarios and the large incremental capacity is then used throughout the entire model horizon. The direct pipeline between Russia and Italy is again not constructed because Italy can satisfy its demand from Algeria and potentially with flows of Russian natural gas via Germany.

5 Conclusions

We have developed a complementarity model of a two-stage market with network utilization and investment. We applied this model to a small data set of the European natural gas market. Our results confirm the finding of earlier studies (e.g., Holz et al., 2008; Egging et al., 2008a) that especially the transport capacity between European countries needs to

[17]This is an argument in favor of a more complex market and modeling framework, with market power between the market stages and an EPEC-type of model.

be expanded. The transport of imports from external suppliers to countries beyond the European border requires sufficient infrastructure which is currently available only with small capacities. In our example, it is economic for all different parameter settings to construct more capacity between Germany, the border country with Russia, on the one hand, and France and Italy on the other hand to deliver Russian natural gas to them. The arcs necessary to transport Norwegian and Algerian natural gas beyond their border countries have high shadow values, but are generally not large enough to cover the investment costs.

Our results also show that the parameter choice is crucial, especially for future demand and for investment costs. Future demand parameters (forecasted quantities, prices) strongly depend on the assumptions with which they are obtained, for example on the future inter-fuel competition and the total energy demand in a climate change situation. Investment costs have been volatile in the past and depend on such factors as global demand for investments (materials, engineering) in the same sector and in other sectors. Hence, for a large-scale simulation model, careful parametrization is necessary.

Our results show the relevance of including the intra-European pipelines and the downstream wholesale market in a model of the European natural gas market. We argue that the depicted two-stage market structure is more representative for the European natural gas market than a sole export market model. To obtain an even more realistic model, the present MCP model should be reformulated as an EPEC model and a solution algorithm be developed. The export and import market could potentially be linked with strategic relations in both directions with bargaining power by the importers vis-à-vis the exporters, and oligopolistic market power by the exporters via the downstream market.

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