The GaMMES model
A generalized Nash-Cournot Model for the N-W.
European Natural Gas Markets with a fuel substitution demand

Séminaire de Recherches en Economie de l'Energie de Paris-Sciences-Lettres
Mercredi 10 Avril 2013

Ibrahim ABADA      Vincent BRIAT      Steven GABRIEL      Olivier MASSOL
EDF R&D,            EDF R&D.          University of Maryland.  IFP-School.
IFP Energies Nouvelles,                       University Paris X.
Background: the EU’s gas dependency

Source: BP Statistical Review 2012
The model: objectives

Mathematical modelling of the natural gas markets using an oligopolistic approach (strategic players owning market powers).

Smeers (2008): a meticulous review of the existing models

- EUGAS- MAGELAN - TIGER
- The Baker Institute World Trade Gas Model

- NATGAS
- GASTALE
- GASMOD
- WGM

Pure and perfect competition modelling.

Oligopolistic approach. Linearity of the demand function. These models do not consider the possible fuels substitution. Long term contracts are exogenous. Double marginalization assumptions.

A wish list:

- An enhanced representation of the demand side (capturing the dynamics, the possible interfuel substitutions).
- Market structure: a more detailed representation of the midstream players.
- Taking into account the long-term contracts aspects endogenously.
Outline

1. Construction of a demand function
   - A System Dynamics approach.

2. The GaMMES model
   - Market structure description.
   - Strategic games and decision variables.
   - Generalised Nash Cournot games and long-term contracts.
   - Storage and transport operators.

Methodology

Moxnes (1986): a SD approach to model to the dynamics of interfuel substitution in the industrial sector.

- a putty-clay model that uses a vintage representation of capital stock to capture the effect of both past and current energy prices on current fuel consumption.

Methodology:

1. Construction of an adapted and updated version of the model
2. Validation: application to model the industrial and total energy consumption between 1978 and 2005 in different countries.
3. Construction of a demand function: a « pseudo data » approach
Fuel choice: a logit representation

At time $t$, the share $s_i$ of fuel $i$ for the new equipment is:

$$ s_i = \frac{e^{-\alpha C_i}}{\sum e^{-\alpha C_i}} $$

where

$$ C_i = \frac{CC_i}{PBT_i} + OO_i + \frac{P_i + Q_{CO_2 i} \cdot P_{CO_2}}{E_i} - PR_i $$

- Capital cost
- Fuel price
- Operating cost
- CO2 price
- Burner Efficiency
- A switching parameter (to be calibrated)
- A relative premium (to be calibrated)
A vintage structure

For each fuel $i$,

- New: $I_i \rightarrow KN_i \rightarrow \frac{KN_i}{T_i}$
- Old: $\frac{KN_i}{T_i} \rightarrow KO_i \rightarrow \frac{KO_i}{T_i}$

Where $I_i = s_i I$

And

Energy demand

$E = \sum_i^{KO_i} \frac{KO_i}{T_i} \times f(ED - K)$

Scrapped old burners

Global capacity of all the burners

$K = \sum_i (KN_i + KO_i)$
Validation

Calibration of the unknown parameters
- initial stock of equipments, switching parameter, fuel premiums

Example: industrial annual fuel consumption (1978, 2008)
Validation: Global consumption

US
total consumption

ktoe $x 10^5$

oil

NG

coal

years

$\alpha = 0.037$

$P_1 = -55$

$P_2 = -11$

$P_3 = 45$

$KN_1^0 = 0$

$KN_2^0 = 4.4 \times 10^5$

$KN_3^0 = 3 \times 10^5$

$KO_1^0 = 0.6 \times 10^5$

$KO_2^0 = 3.17 \times 10^4$

$KO_3^0 = 0.2 \times 10^4$

real data

model estimation
Construction of a demand function

A « pseudo data » approach : ceteris paribus simulation of the instantaneous relation $Q_{gas}(P_{gas})$

Canada, industrial sector, natural gas, 2009
Construction of a demand function

- A « pseudo data » approach: ceteris paribus simulation of the instantaneous relation $Q_{\text{gas}}(P_{\text{gas}})$

Canada, industrial sector, natural gas, 2009

$$q(p) = \beta + \delta \cdot (1 - \tanh(\gamma \cdot (p - p_c)))$$

- The "clay" effect
- The price of a composite competing fuel
- An amplitude parameter
- A curvature parameter
Outline

1. Construction of a demand function

   → A System Dynamics approach.

2. The GaMMES model

   → Market structure description.
   → Strategic games and decision variables.
   → Generalised Nash Cournot games and long-term contracts.
   → Storage and transport operators.

The model: market and strategic players

Two types of strategic players

- **Upstream ones**: Producers and dedicated traders. E.g. Russia and Gazprom.
- **Downstream ones**: The independent traders sell back their gas to the end-users. E.g. Ruhrgas-e one, GDFSuez etc.

A producer can either

- establish long-term contracts (LTCs) with the independent traders
- or sell his gas directly to the end-users.

**LTC**: a bilateral contract between a producer and an independent trader. The unit selling/purchase price and the quantity are **endogenously determined**.

**The demand side**: an aggregated demand function for each market.

**The independent/dedicated traders** interact thanks to a **Generalized Nash-Cournot** competition on the final markets: they can exert market power.
The model: description

The model is dynamic: horizon 40 years.

- Two "seasons by year": high/low demand regimes.
  - summer/winter production
  - summer/winter prices spread

Upstream:
- Each producer has access to a certain number of fields with different production cost functions.
- Each producer has the possibility to invest in order to increase the production capacity of each field.
- The fields flexibility is taken into consideration (maximal spread between summer/winter productions).
The model: production costs

We choose a Golombok functional form to model the production cost on a given field.

If at year \( t \) the production is \( q \), the marginal production cost is:

\[
\frac{dc}{dQ}(t, q) = a + bq + c \ln \left( \frac{Q - q}{q} \right)
\]

The parameters \( a, b, \) and \( c \) depend on the previous produced quantities (before year \( t \)).

\( Q \) is the finite reserve of the considered field.

Dynamically, the total cost can be rewritten as follows

\[
C_{total} = \sum_{t} \delta^t \left( c \left( \sum_{t' < t} q_{t'} \right) - c \left( \sum_{t' < t} q_{t'} \right) \right)
\]

\( \delta \) Discount factor

\( q_t \) Quantity produced at year \( t \)

Main advantages:

It takes into account the exhaustible nature of the gas resource.

Convexity of the production function.
The model: transport and storage

**Transport**

We model a global transport operator whose objective is to **minimize the overall transport/congestion costs** over the network.

The flows capacities through the arcs can be increased dynamically thanks to investments made by the pipeline operator.

**Storage**

We model a set of storage sites nodes operated by a regulated storage operator.

Each independent trader is able to store/withdraw natural gas to satisfy high demand regimes (with associated transport/reservation/injection/withdrawal unit costs).

The storage capacities can be increased dynamically thanks to investments made by the storage operator.
The model: decision variables

The model details the optimization programs of each player.

**The producers and their dedicated traders** control:
- The quantities produced each year, from each field and at each season.
- The volumes sold to the independent traders using LTCs.
- The volume sold on the spot markets (to the end-users).
- The production investments.

**The independent traders** control:
- The volumes sold to the end-users on the spot market at each year and each season.
- The stored and withdrawn quantities at each storage node.

**The transport operator** controls:
- The flows through the arcs of the network.
- The infrastructure capacity investments.

**The storage operator** controls:
- The volumes stored at each site.
- The storage capacity investments.
The model formulation

Exogenous factors

$P$ set of producers-dedicated traders
$I$ set of independent traders
$D$ set of gas consuming countries in the downstream market
  (no distinction between the sectors) $D \subset N$
$T$ time $T = \{0, 1, 2, ..., Num\}$
$M$ set of seasons. Off-peak (low-consumption) and peak (high-consumption) regimes
$F$ set of all the gas production fields. $F \subset N$
$N$ set of the nodes
$S$ set of the storage sites $S \subset N$
$A$ set of the arcs (topology)
Endogenous variables

\( x_{mfp}^t \): quantity of gas produced by \( p \) from field \( f \) for the end-use market \( d \), year \( t \), season \( m \) in Bcm

\( z_{p_{mfp}}^t \): quantity of gas produced by \( p \) from field \( f \) dedicated to the long-term contract with trader \( i \), year \( t \), season \( m \) in Bcm

\( z_{i_{mpi}}^t \): quantity of gas bought by trader \( i \) from producer \( p \) with a long-term contract year \( t \), season \( m \) in Bcm

\( u_{p_i} \): quantity of gas sold by producer \( p \) to trader \( i \) with a long-term contract, each year in Bcm

\( u_{i_{p_i}} \): quantity of gas bought by trader \( i \) from producer \( p \) on the long-term contract, each year in Bcm

\( y_{mid}^t \): quantity of gas sold by \( i \) to the market \( d \), year \( t \), season \( m \) in Bcm

\( ip_{fp}^t \): producer \( p \)'s increase of field \( f \)'s production capacity, due to investments in production, year \( t \) in Bcm/time unit

\( q_{mfp}^i \): production of producer \( p \) from field \( f \), year \( t \), season \( m \) in Bcm

\( p_{imd}^t \): market \( d \)'s gas price, result of the Cournot competition between all the traders, year \( t \), season \( m \) in $/cm
\( \eta_{pi} \) long-term contract price contracted between producer \( p \) and trader \( i \) in \$/cm

\( r_{is}^t \) amount of storage capacity reserved by trader \( i \) at site \( s \), year \( t \) in Bcm

\( in_{is}^t \) volume injected by trader \( i \) at site \( s \), year \( t \) in Bcm

\( is_s^t \) increase of storage capacity at site \( s \), year \( t \) due to the storage operator investments in Bcm/time unit

\( ik_a^t \) increase of the pipeline capacity through arc \( a \), year \( t \), due to the TSO investments in Bcm/time unit

\( fP_{mpa}^t \) gas quantity that flows through arc \( a \) from producer \( p \) year \( t \), season \( m \) in Bcm

\( fi_{mia}^t \) gas quantity that flows through arc \( a \) from trader \( i \) year \( t \), season \( m \) in Bcm

\( \tau_{ma}^t \) the dual variable associated with arc \( a \) capacity constraint year \( t \), season \( m \) in \$/cm. It represents the congestion transportation cost over arc \( a \)
Producers' maximization program and feasibility set

\[
\begin{align*}
\text{Max} & \quad \sum_{t,m,f,i} \delta^t \eta_{pi}(z p_{t,m,f,p,i}^t) \\
& + \sum_{t,m,f,d} \delta^t \left( p_{t,m,f,p,d}^t \left( x_{t,m,f,p,d}^t + x_{t,m,f,p,d}^t \right) \right) x_{t,m,f,p,d}^t \\
& - \sum_{t,f} \delta^t P_{cf} \left( \sum_{t' \leq t} \sum_{m} \hat{q}_{t,m,f,p}^{t'} R_{f,f}^{t'} \right) \\
& + \sum_{t,f} \delta^t P_{cf} \left( \sum_{t' < t} \sum_{m} \hat{q}_{t,m,f,p}^{t'} R_{f,f}^{t'} \right) \\
& - \sum_{t,f} \delta^t I p_{f} i p_{f}^{t} \\
& - \sum_{t,m,p,a} \delta^t (T c_{a} + \tau_{m,a}^t) p_{m,p,a}^t 
\end{align*}
\]
\[ \forall t, f, \sum_p \sum_{t' \leq t} \sum_m q_{mfp}^{t'} - Rf_t \leq 0 \]

\[ \forall t, f, m, \sum_p q_{mfp}^t - \left(Kf_j(1 - dep_j)^t \right) \]
\[ - \sum_p \sum_{t' \leq t - delay_p} ip_{fp}^{t'}(1 - dep_f)^{t-t'} \leq 0 \]

\[ \forall t, m, f, -q_{mfp}^t + \left(\sum_i zp_{mfp, i}^t + \sum_d x_{mfpd}^t\right) \leq 0 \]

\[ \forall t, f, \sum_p \sum_m (-1)^m q_{mfp}^t - fl_t \leq 0 \]

\[ \forall t, f, \sum_p \sum_m ((-1)^m q_{mfp}^t) - fl_t \leq 0 \]

\[ \forall t, f, d, m, x_{mfpd}^t - OfpH \leq 0 \]

\[ \forall t, f, i, m, zp_{mfp, i}^t - OfpH \leq 0 \]

\[ \forall t, f, m, q_{mfp}^t - OfpH \leq 0 \]

\[ \forall t, f, ip_{fp}^t - OfpH \leq 0 \]

\[ \forall t, m, n, \sum_a M6anfp_{mpo}^t (1 - loss_a) - \sum_a M5anfp_{mpo}^t - \sum_f M1fnq_{mpf}^t + \sum_d \sum_f M3dnx_{mfpd}^t \]
\[ - \sum_i \sum_f M2lnzp_{mfp, i}^t = 0 \]

\[ \forall t, i, up_{pi}^t - \sum_{f, m} zp_{mfp, i}^t = 0 \]

\[ \forall i, up_{pi}^t - up_{pi}^t = 0 \]

\[ \forall t, m, d, i, f, zp_{mfp, i}^t, x_{mfpd}^t, ip_{fp}^t, q_{mfp}^t, up_{pi}^t \geq 0 \]

Resource constraint

Production capacity constraint (including investments)

Production > sales

Flexibility constraints

Transportation flows management

\[ sales_{p, i}^t = purchases_{i, p}^t \]
Deriving the price of a LTC

Sales from $p$ to $i$ = purchases of $i$ from $p$

\[ \forall p, \ i, \ u_{pi} = u_{pi} - (\eta_{pi}) \]

Dual variable

Dual variable = shadow LTC price between $p$ and $i$
The pipeline operator optimization program and feasibility set

Min

\[
\sum_{t,m,a} \delta^t \left( Tc_a + \tau_{ma}^t \right) \sum_p f_{m}^t \\text{m} \text{a} + \sum_{t,m,a} \delta^t \left( Tc_a + \tau_{ma}^t \right) \sum_i f_{i}^t \\text{m} \text{a} i + \sum_{t,a} \delta^t I k_a \alpha k_a^t
\]

such that:

\forall t, m, a.
\[\sum_p f_{m}^t \\text{m} \text{a} + \sum_i f_{i}^t \\text{m} \text{a} i - \left( Tk_a + \sum_{t \leq t \text{delay}_{i}} \tau_{ma}^t \right) \leq 0 \quad (\tau_{ma}^t)\]

\forall t, m, p, n.
\[\sum_a M_{6an} f_{m}^t \\text{m} \text{a} p_n (1 - loss_a) - \sum_a M_{5an} f_{m}^t \\text{m} \text{a} p_n + \sum_f M_{1 fn} g_{mpf}^t - \sum_d \sum_f M_{3dn} x_{mfpd}^t - \sum_i \sum_f M_{2in} p_{mpfi}^t = 0 \quad (\alpha_p^t \text{mpn})\]

\forall t, m, i, n.
\[\sum_a M_{6an} f_{i}^t \\text{m} \text{a} i (1 - loss_a) - \sum_a M_{5an} f_{i}^t \\text{m} \text{a} i - \sum_d M_{3dn} y_{mid}^t + \sum_p M_{2in} z_i^t m_{p} = 0 \quad (\alpha_i^t \text{min})\]

\forall t, m, a, p, i.
\[f_{m}^t \\text{m} \text{a}, f_{i}^t \\text{m} \text{a} i, k_a^t \geq 0\]

Transport and congestion costs

Infrastructure investment costs

Capacity constraint (including investments)

Flows balance through the network due to producers decisions

Flows balance through the network due to independent traders decisions

Dual variable = shadow price for the congestion cost through arc a
The storage operator optimization program and feasibility set

\[ \text{Min} \quad \sum_{t,s} \delta^t I_s s^t_i s^t_s \]

such that:

\[ \forall t, s, \quad \sum_i r^t_{is} - K_s - \sum_{t' \leq t - \text{delay}_s} s^t_s \leq 0 \]

\[ \forall t, s, \quad s^t_s \geq 0 \]
Paving the way to a solution

We need to write the first order conditions to solve the model optimization programs.

K.K.T. conditions.

Demonstration of the concavity of all the objective functions to ensure the existence of the Nash-Cournot equilibrium.

The model is formulated as a Mixed Complementarity Problem (M.C.P.).

The feasibility set of each player depends on the decision variables of some other players.

Generalized Nash-Cournot game.

A G.N.C. game has usually an infinite set of solutions.

Necessity to find and characterize the solution we look for (economic interpretation etc.).

Distinction VI / QVI formulations and solutions.

The model has been solved using the PATH solver.
Outline

1. Construction of a demand function
   A System Dynamics approach.

2. The GaMMES model
   Market structure description.
   Strategic games and decision variables.
   Generalised Nash Cournot games and long-term contracts.
   Storage and transport operators.

Data

- Reserves and existing production and transport infrastructure. Source: MAGELAN, Köln university.

- Production and transport costs: CAPEX from MAGELAN (updated using CERA’s inflation index UCCI).

- The demand calibration: the industrial price is used as a proxy for the market price. Source: OECD. (IEA, Energy statistics).


- Long-term marginal production cost curves, reserves and scenarios of the production capacity expansion. Differentiation by country.
<table>
<thead>
<tr>
<th>Consumers</th>
<th>Producers</th>
<th>Time</th>
<th>Seasons</th>
</tr>
</thead>
<tbody>
<tr>
<td>France</td>
<td>Russie</td>
<td>2000-2045</td>
<td>Winter</td>
</tr>
<tr>
<td>Germany</td>
<td>Algeria</td>
<td></td>
<td>Summer</td>
</tr>
<tr>
<td>UK</td>
<td>Netherlands</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Belgium</td>
<td>Norway</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Netherlands</td>
<td>United Kingdom</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Poland</td>
<td>Poland</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CZ Republic</td>
<td>Germany</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Italy</td>
<td>France</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Denmark</td>
<td>Caspian area</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Switzerland</td>
<td>Qatar</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Austria</td>
<td>Rest of the world</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Tests of the model: 2005-2010

Consumption

Price

Error

10%

9%
Shale gas in Europe

Case 0
Impact on the European production

Natural gas sales

Sales Bcm/year

2005 2010 2015 2020 2025 2030

- Shale
- UK
- NO
- NL
Shale gas in Europe

Case 0

Impact on the production

Russia

Algeria

Netherlands

Norway
Shale gas in Europe

Case 0

Impact on the production

UK

Poland

Germany

France
Shale gas in Europe

Case 0

Impact on the production

Caspian area

Quatar

Rest of the world
Shale gas in Europe

Case 0
Impact on the production

11% of shale gas in the production in 2030
Shale gas in Europe

Case 0

Impact on the consumption

France

Germany

UK

Belgium
Shale gas in Europe

Case 0

Impact on the consumption
Shale gas in Europe

Case 0

Impact on the consumption
Shale gas in Europe

Case 0

Impact on the prices
Shale gas in Europe

Case 0

Impact on the prices

Netherlands

Poland

Cz Republic

Italy
Shale gas in Europe

Case 0

Impact on the prices

Danmark

Price $/m²

2000 2010 2020 2030 2040

Switzerland

Price $/m²

2000 2010 2020 2030 2040

Austria

Price $/m²

2000 2010 2020 2030 2040
Conclusions

We have developed a dynamic Generalized Nash-Cournot model to describe the natural gas markets.

We have applied our model to the European gas trade in order to study the impact of shale gas, if it is produced.

The reference scenario suggests that the shale gas production will reach 11% of the total production in Europe in 2030.

The shale gas will reduce the prices by 11% and increase the consumption by 12% on average in Europe by 2030.

The shale gas will reduce the Russian market share by 9%, principally because of Poland.
Thank you for your attention