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

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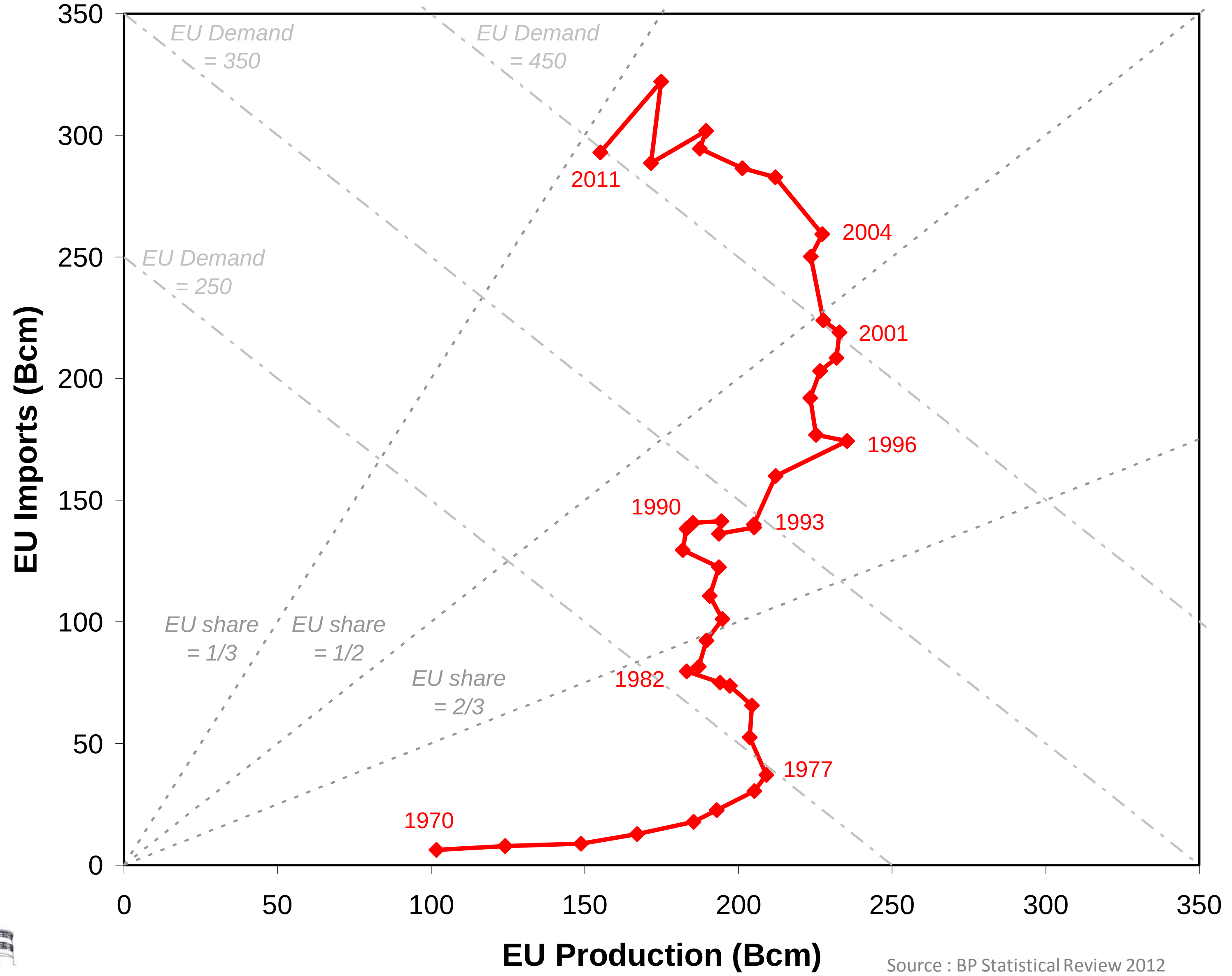
Background: the EUôs gas dependency



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*

Pure and perfect competition modelling.

- → *NATGAS*
- → *GASTALE*
- → *GASMOD*
- → *WGM*

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:

ÅAn enhanced representation of the demand side (capturing the dynamics, the possible interfuel substitutions).

ÅMarket structure: a more detailed representation of the midstream players.

ÅTaking 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.

3. Shale gas in Europe.

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:

A switching parameter
(to be calibrated)

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

where

Capital cost

Fuel price

CO_2 price

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

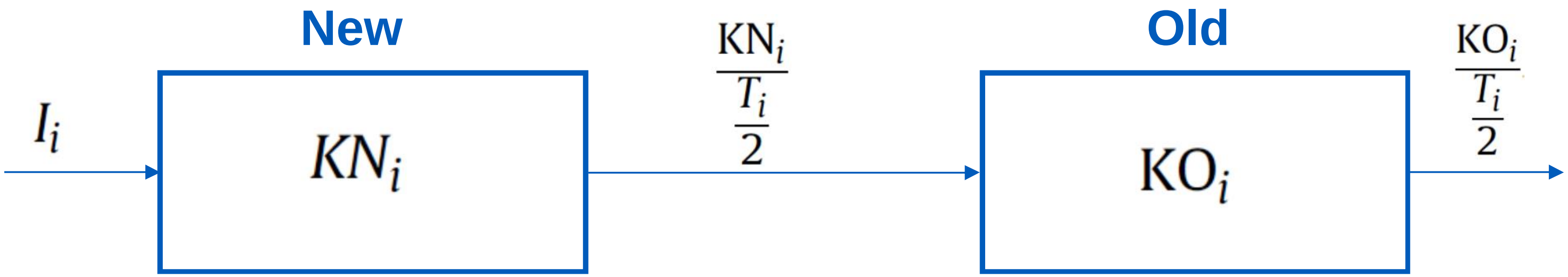
Operating cost

Burner Efficiency

A relative premium
(to be calibrated)

A vintage structure

- for each fuel i,



where $I_i = s_i I$

and

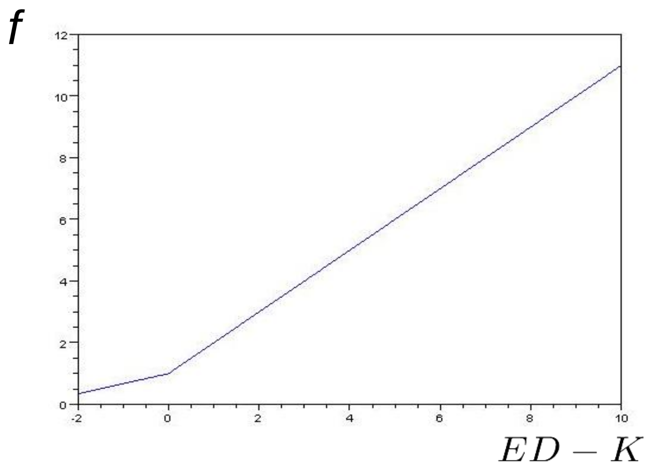
Energy demand

$$I = \sum_i \frac{KO_i}{\frac{T_i}{2}} \times f(ED - K)$$

Scrapped old burners

Global capacity of all the burners

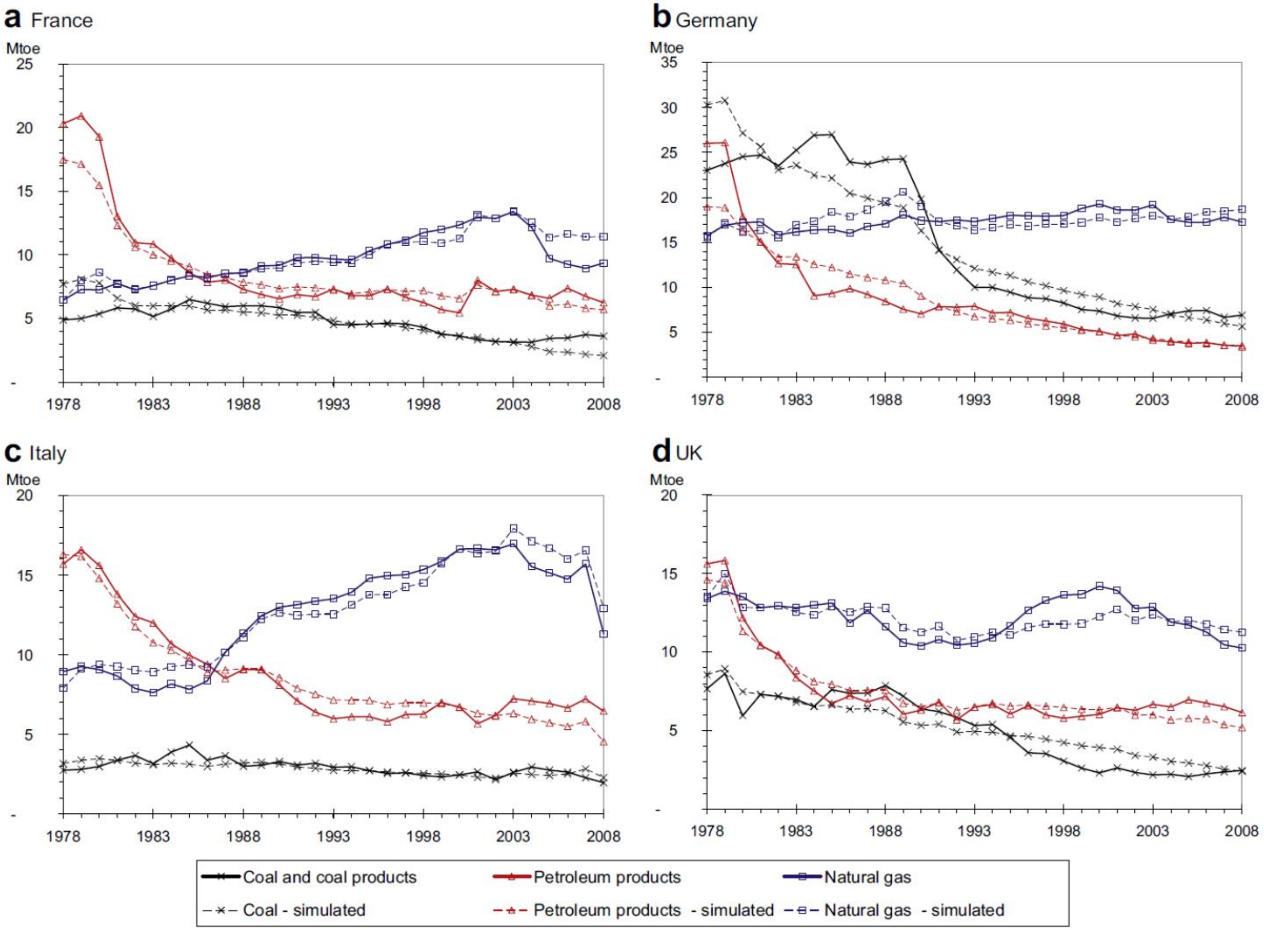
$$K = \sum_i (KN_i + KO_i)$$



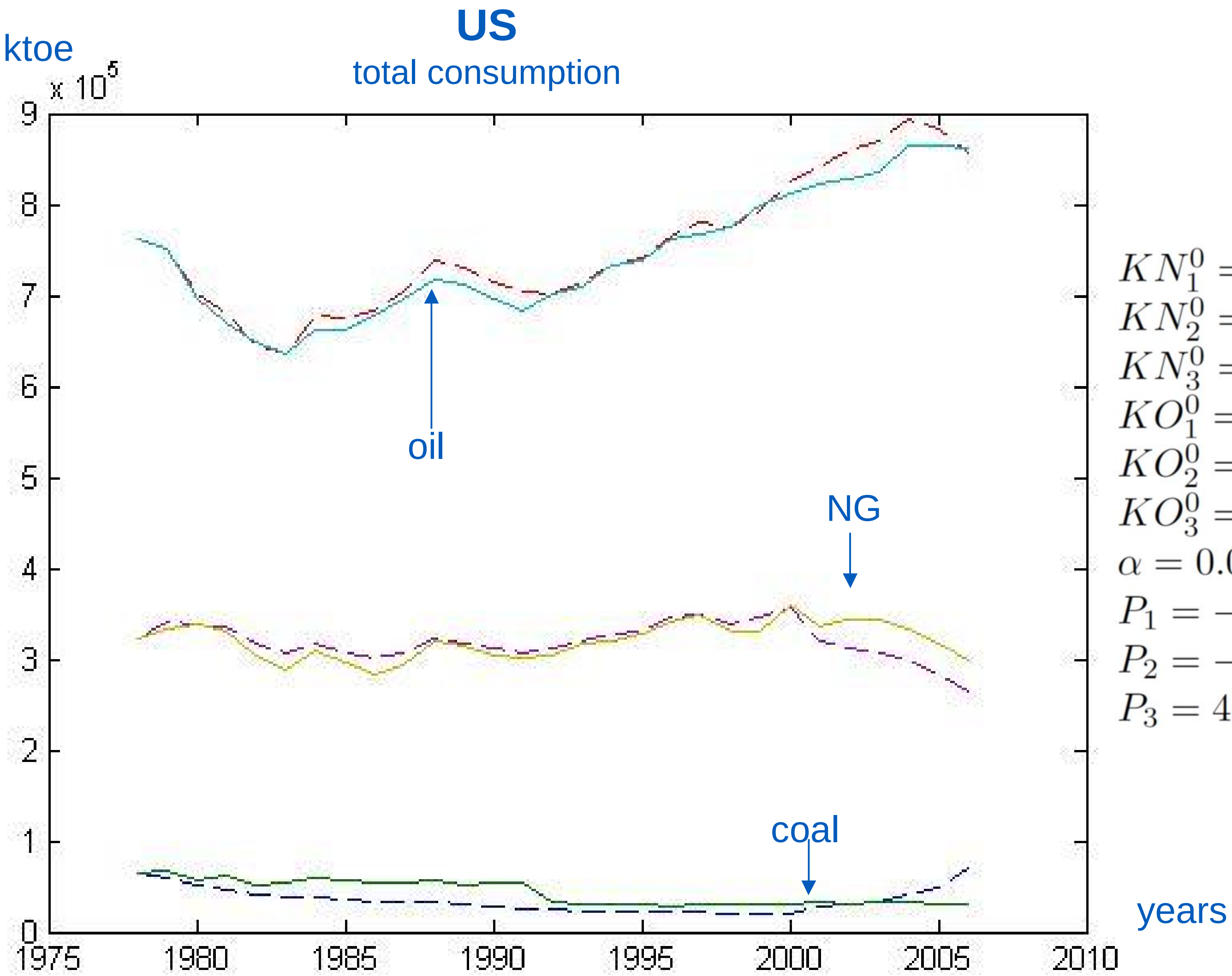
Validation

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

Example: industrial annual fuel consumption (1978, 2008)



Validation: Global consumption



$$KN_1^0 = 0$$
$$KN_2^0 = 4.4\ 10^5$$
$$KN_3^0 = 3\ 10^5$$
$$KO_1^0 = 0.6\ 10^5$$
$$KO_2^0 = 3.17\ 10^4$$
$$KO_3^0 = 0.2\ 10^4$$
$$\alpha = 0.037$$
$$P_1 = -55$$
$$P_2 = -11 \quad \text{\$/tep}$$
$$P_3 = 45$$

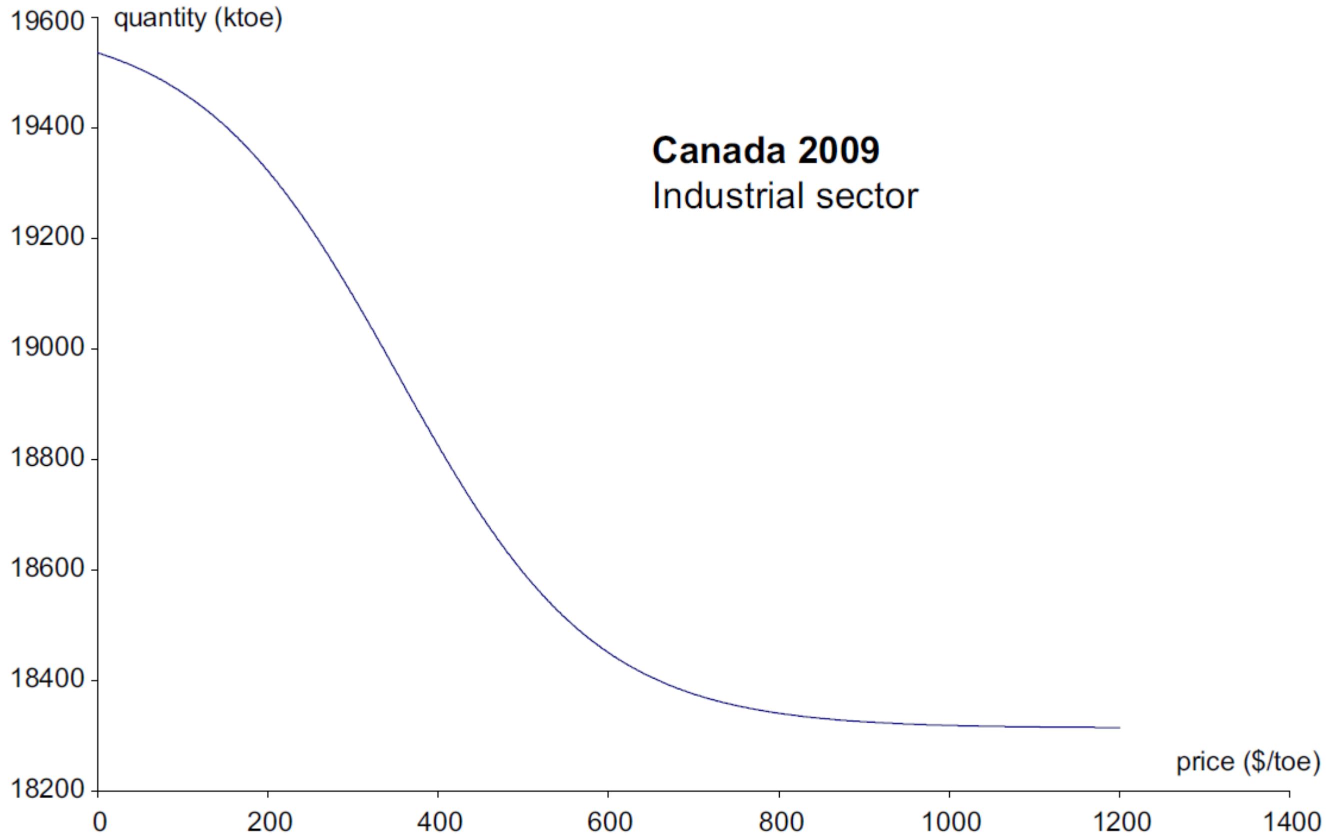
——— real data

– – – – – – model estimation

Construction of a demand function

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

Canada, industrial sector, natural gas, 2009



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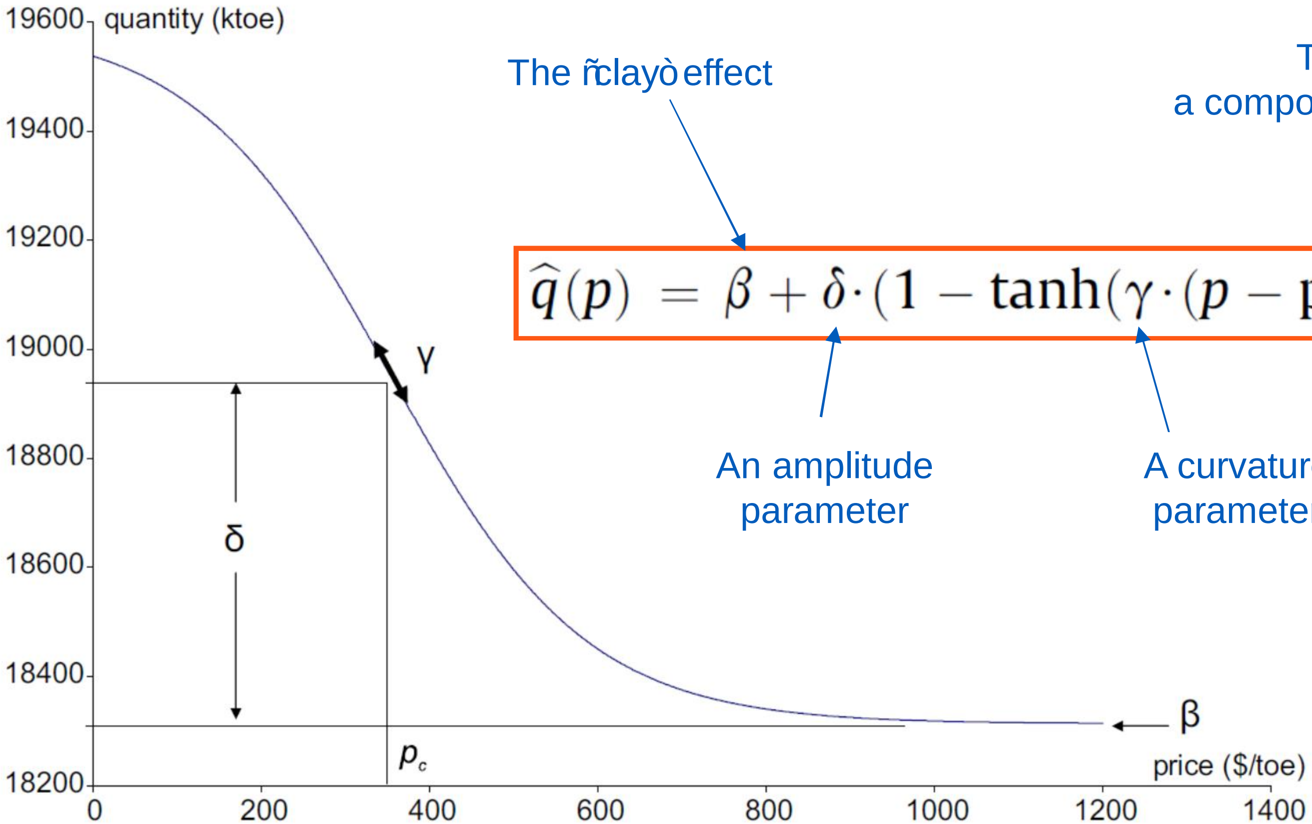

The « clay » effect

The price of a composite competing fuel

$$\boxed{\widehat{q}(p) = \beta + \delta \cdot (1 - \tanh(\gamma \cdot (p - \mathrm{pc})))}$$

An amplitude parameter

A curvature parameter

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The model: market and strategic players

- Two type of strategic players

  → The **upstream ones**: Producers and dedicated traders. E.g. Russia and Gazprom.

  → The **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.

Å Two "seasons by year": high/low demand regimes.

⟹ summer/winter production

⟹ summer/winter prices spread

Upstream :

ÅEach producer has access to a certain number of fields with different production cost functions.

ÅEach producer has the possibility to invest in order to increase the production capacity of each field.

ÅThe fields flexibility is taken into consideration (maximal spread between summer/winter productions).

The model: production costs

ÅWe choose a Golombek functional form to model the production cost on a given field.

ÅIf at year *t* the production is *q*, the marginal production cost is:

$$\boxed{\frac{\mathrm{d}c}{\mathrm{d}Q}(t,q) = a + bq + c\,\ln\left(\frac{Q-q}{q}\right)}$$

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

Å*Q* is the finite reserve of the considered field.

ÅDynamically, the total cost can be rewritten as follows $C_{total} = \sum_t \delta^t \left(c(\sum_{t' \leq t} q_{t'}) - c(\sum_{t'<t} q_{t'}) \right)$

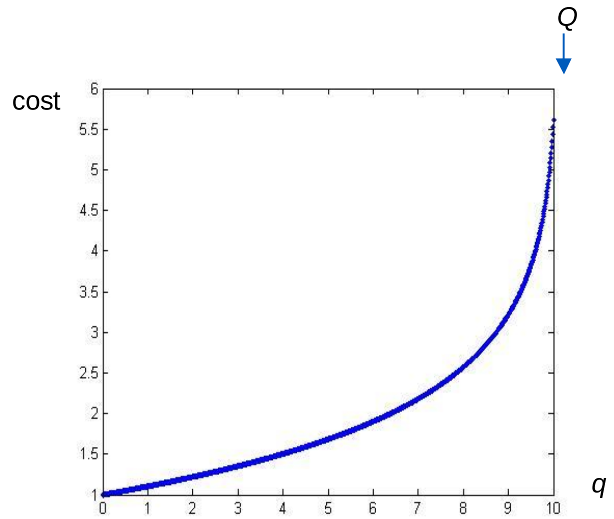
δ Discount factor

q_t Quantity produced at year *t*

Main advantages:

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

ÅConvexity of the production function.



The model: transport and storage

Transport

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

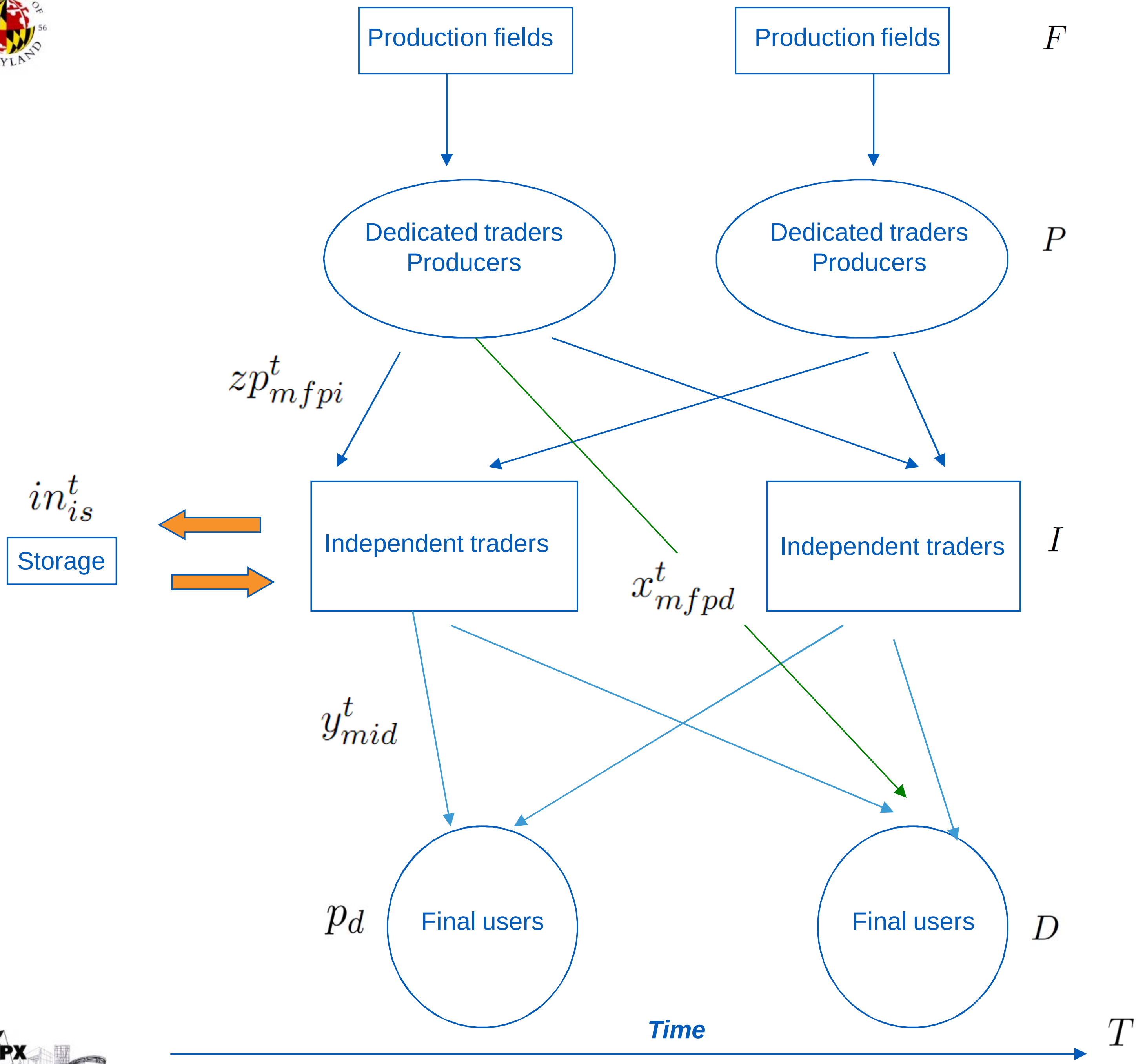
ÅThe flows capacities through the arcs can be increased dynamically thanks to investments made by the pipeline operator.

Storage

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

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

ÅThe storage capacities can be increased dynamically thanks to investments made by the storage operator.



Production fields
Production fields
F
Dedicated traders Producers
Dedicated traders Producers
P
Upstream market
zp^t_{mfpi}
in^t_{is}
Storage
Independent traders
Independent traders
I
x^t_{mfpd}
y^t_{mid}
Downstream market
p_d
Final users
Final users
D
Time
T

The model: decision variables

ÅThe model details the optimization programes of each player.

The producers and their dedicated traders control:

ÅThe quantities produced each year, from each field and at each season.

ÅThe volumes sold to the independent traders using LTCs.

ÅThe volume sold on the spot markets (to the end-users).

ÅThe production investments.

The independent traders control:

ÅThe volumes sold to the end-users on the spot market at each year and each season.

ÅThe stored and withdrawn quantities at each storage node.

The transport operator controls:

ÅThe flows through the arcs of the network.

ÅThe infrastructure capacity investments.

The storage operator controls:

ÅThe volumes stored at each site.

ÅThe storage capacity investments.

Generalized Nash-Cournot problem

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^t_{mfpd}	quantity of gas produced by p from field f for the end-use market d, year t, season m in Bcm
zp^t_{mfpi}	quantity of gas produced by p from field f dedicated to the long-term contract with trader i, year t, season m in Bcm
zi^t_{mpi}	quantity of gas bought by trader i from producer p with a long-term contract year t, season m in Bcm
up_{pi}	quantity of gas sold by producer p to trader i with a long-term contract, each year in Bcm
ui_{pi}	quantity of gas bought by trader i from producer p on the long-term contract, each year in Bcm
y^t_{mid}	quantity of gas sold by i to the market d, year t, season m in Bcm
ip^t_{fp}	producer p's increase of field f's production capacity, due to investments in production, year t in Bcm/time unit
q^t_{mfp}	production of producer p from field f, year t, season m in Bcm
p^t_{md}	market d's gas price, result of the Cournot competition between all the traders, year t, season m in \$/cm

η_{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
τ_{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

Max

$$\sum_{t,m,f,i} \delta^t \eta_{pi}(zp^t_{mfpi})$$

LTC sales

$$+ \sum_{t,m,f,d} \delta^t \left(p^t_{md}(x^t_{mfpd} + \overline{x^t_{mfpd}}) \right) x^t_{mfpd}$$

Spot markets sales (market power)

$$- \sum_{t,f} \delta^t Pc_f \left(\sum_{t' \leq t} \sum_{m} q^{t'}_{mfp}, Rf_f \right)$$

$$+ \sum_{t,f} \delta^t Pc_f \left(\sum_{t' < t} \sum_{m} q^{t'}_{mfp}, Rf_f \right)$$

Production costs

$$- \sum_{t,f} \delta^t Ip_f ip^t_{fp}$$

Production investments costs

$$- \sum_{t,m,p,a} \delta^t ((Tc_a + \tau^t_{ma}) fp^t_{mpa})$$

Transportation costs

$$\forall t,\ f,\quad \sum_{p}\sum_{t'\leq t}\sum_{m} q^{t'}_{mfp} - Rf_f \leq 0$$

Resource constraint

$$\forall t,\ f,\ m,\quad \sum_{p} q^{t}_{mfp} - Kf_f(1-dep_f)^t - \sum_{p}\sum_{t'\leq t-delay_p} ip^{t'}_{fp}(1-dep_f)^{t-t'} \leq 0$$

Production capacity constraint (including investments)

$$\forall t,\ m,\ f,\quad -q^{t}_{mfp} + \left(\sum_{i} zp^{t}_{mfpi} + \sum_{d} x^{t}_{mfpd}\right) \leq 0$$

Production > sales

$$\forall t,\ f\quad \sum_{m}\sum_{p}((-1)^m q^{t}_{mfp}) - fl_f \leq 0$$

$$\forall t,\ f,\quad -\sum_{m}\sum_{p}((-1)^m q^{t}_{mfp}) - fl_f \leq 0$$

Flexibility constraints

$$\forall t,\ f,\ d,\ m,\quad x^{t}_{mfpd} - O_{fp}H \leq 0$$

$$\forall t,\ f,\ i,\ m,\quad zp^{t}_{mfpi} - O_{fp}H \leq 0$$

$$\forall t,\ f,\ m,\quad q^{t}_{mfp} - O_{fp}H \leq 0$$

$$\forall t,\ f,\quad ip^{t}_{fp} - O_{fp}H \leq 0$$

$$\forall t,\ m,\ n,\quad \sum_{a} M6_{an}fp^{t}_{mpa}(1-loss_a) - \sum_{a} M5_{an}fp^{t}_{mpa} + \sum_{f} M1_{fn}q^{t}_{mpf} - \sum_{d}\sum_{f} M3_{dn}x^{t}_{mfpd} - \sum_{i}\sum_{f} M2_{in}zp^{t}_{mfpi} = 0$$

Transportation flows management

$$\forall t,\ i,\quad up_{pi} - \sum_{f,m} zp^{t}_{mfpi} = 0$$

$$\forall\ i,\quad ui_{pi} - up_{pi} = 0$$

$$sales^{t,m}_{p\longrightarrow i} = purchases^{t,m}_{i\longrightarrow p}$$

$$\forall t,\ m,\ d,\ i,\ f,\quad zp^{t}_{mfpi},\ x^{t}_{mfpd},\ ip^{t}_{fp},\ q^{t}_{mfp},\ up_{pi} \geq 0$$

Deriving the price of a LTC

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

$$\forall p,\ i,\ ui_{pi} = up_{pi} \text{ ------------ } (\eta_{pi})$$

Dual variable

Dual variable = shadow LTC price between *p* and *i*

The pipeline operator optimization program and feasibility set

Min

$$\boxed{\begin{aligned}&\left.\begin{aligned}&\sum_{t,m,a}\delta^t\left(Tc_a+\tau^t_{ma}\right)\sum_p fp^t_{mpa}\\&+\sum_{t,m,a}\delta^t\left(Tc_a+\tau^t_{ma}\right)\sum_i fi^t_{mia}\end{aligned}\right\}\\&+\sum_{t,a}\delta^t Ik_a ik^t_a\end{aligned}}$$

Transport and congestion costs

Infrastructure investment costs

such that:

$$\begin{aligned}
&\forall t,\ m,\ a, && \sum_p fp^t_{mpa}+\sum_i fi^t_{mia}-\left(Tk_a+\sum_{t'\le t-delay_i} ik^{t'}_a\right) \le 0 \quad (\tau^t_{ma})\\
&\forall t,\ m,\ p,\ n, && \sum_a M6_{an} fp^t_{mpa}(1-loss_a)-\sum_a M5_{an} fp^t_{mpa}\\
& && +\sum_f M1_{fn} q^t_{mpf}-\sum_d\sum_f M3_{dn} x^t_{mfpd}\\
& && -\sum_i\sum_f M2_{in} zp^t_{mfpi} = 0 \quad (\alpha p^t_{mpn})\\
&\forall t,\ m,\ i,\ n, && \sum_a M6_{an} fi^t_{mia}(1-loss_a)-\sum_a M5_{an} fi^t_{mia}\\
& && -\sum_d M3_{dn} y^t_{mid}+\sum_p M2_{in} zi^t_{mpi}\\
& && -(-1)^m\sum_s M4_{sn} in^t_{is} = 0 \quad (\alpha i^t_{min})\\
&\forall t,\ m,\ a,\ p,\ i, && fp^t_{mpa},\ fi^t_{mia},\ ik^t_a \ge 0
\end{aligned}$$

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

$$\text{Min} \quad \sum_{t,s} \delta^t I s_s i s_s^t$$

Storage investment costs

such that:

$$\forall t,\ s, \quad \sum_i r_{is}^t - K s_s - \sum_{t' \leq t - delay_s} i s_s^{t'} \leq 0$$

Storage capacity constraint (including investments)

$$\forall t,\ s, \quad i s_s^t \geq 0$$

Paving the way to a solution

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

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3. Shale gas in Europe.

Data

- Reserves and existing production and transport infrastructure.
source: MAGELAN, Koln university.
Capacity expansion's depreciation: MAGELAN/ Söderbergh (2010). (Energy Policy)

- 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).

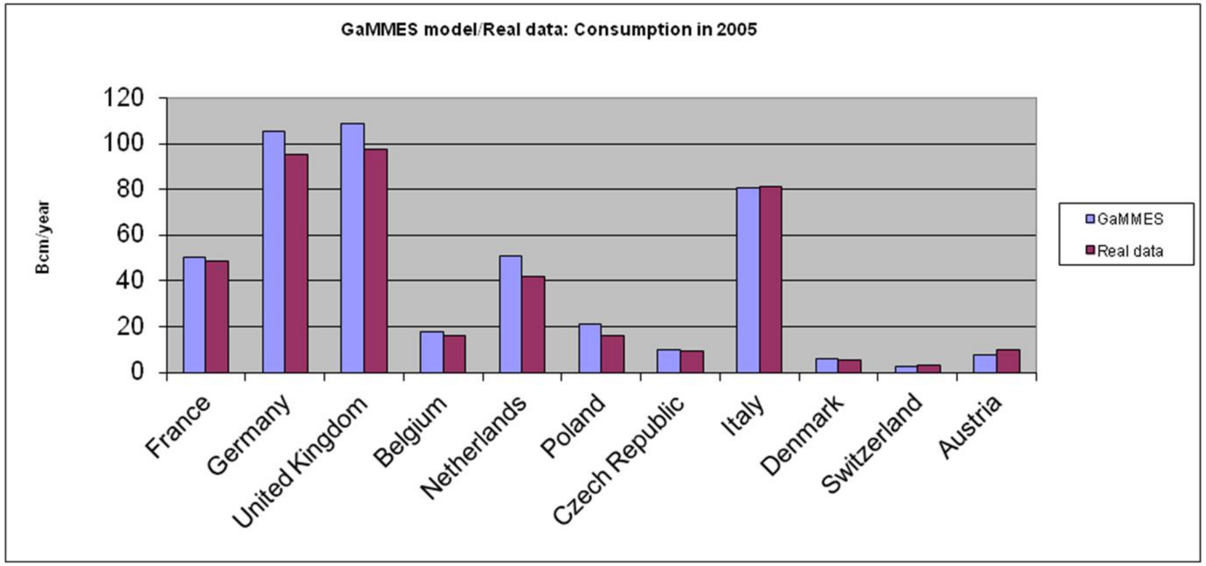
Shale gas: « Breaking with convention », CERA, october 2010.

- Long-term marginal production cost curves, reserves and scenarios of the production capacity expansion. Differenciation by country.

Perimeter

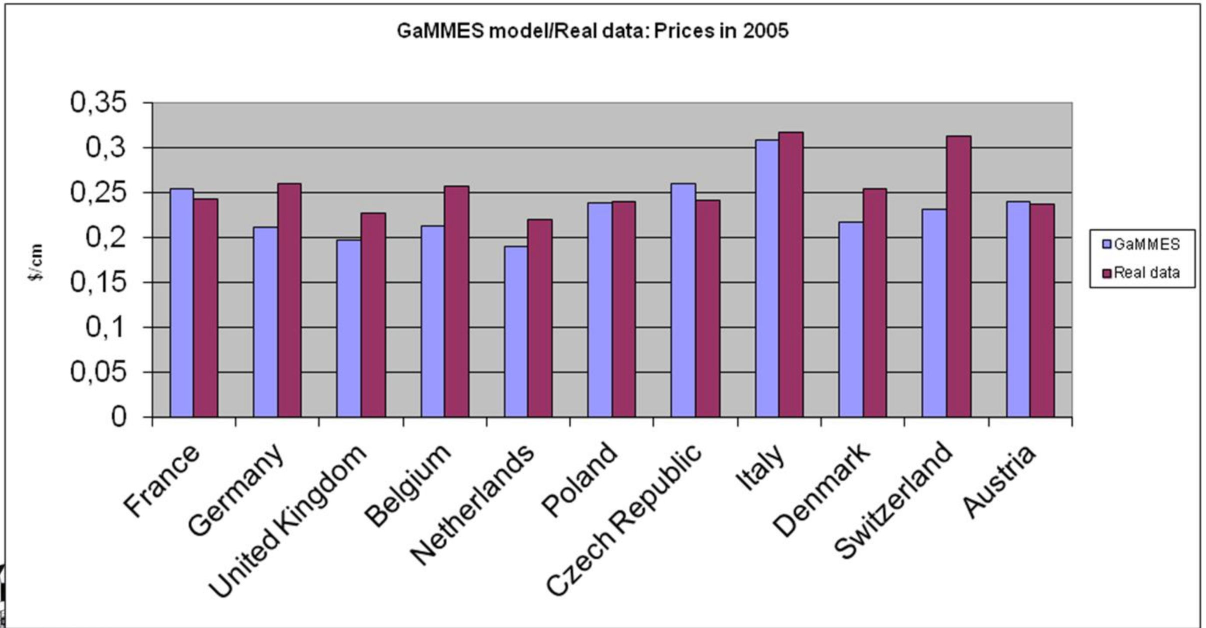
Consumers	Producers	Time	Seasons
France	Russie	2000-2045	Winter
Germany	Algeria		Summer
UK	Netherlands		
Belgium	Norway		
Netherlands	United Kingdom		
Poland	Poland		
CZ Republic	Germany		
Italy	France		
Denmark	Caspian area		
Switzerland	Qatar		
Austria	Rest of the world		

Tests of the model : 2005-2010



Consumption Error

10%



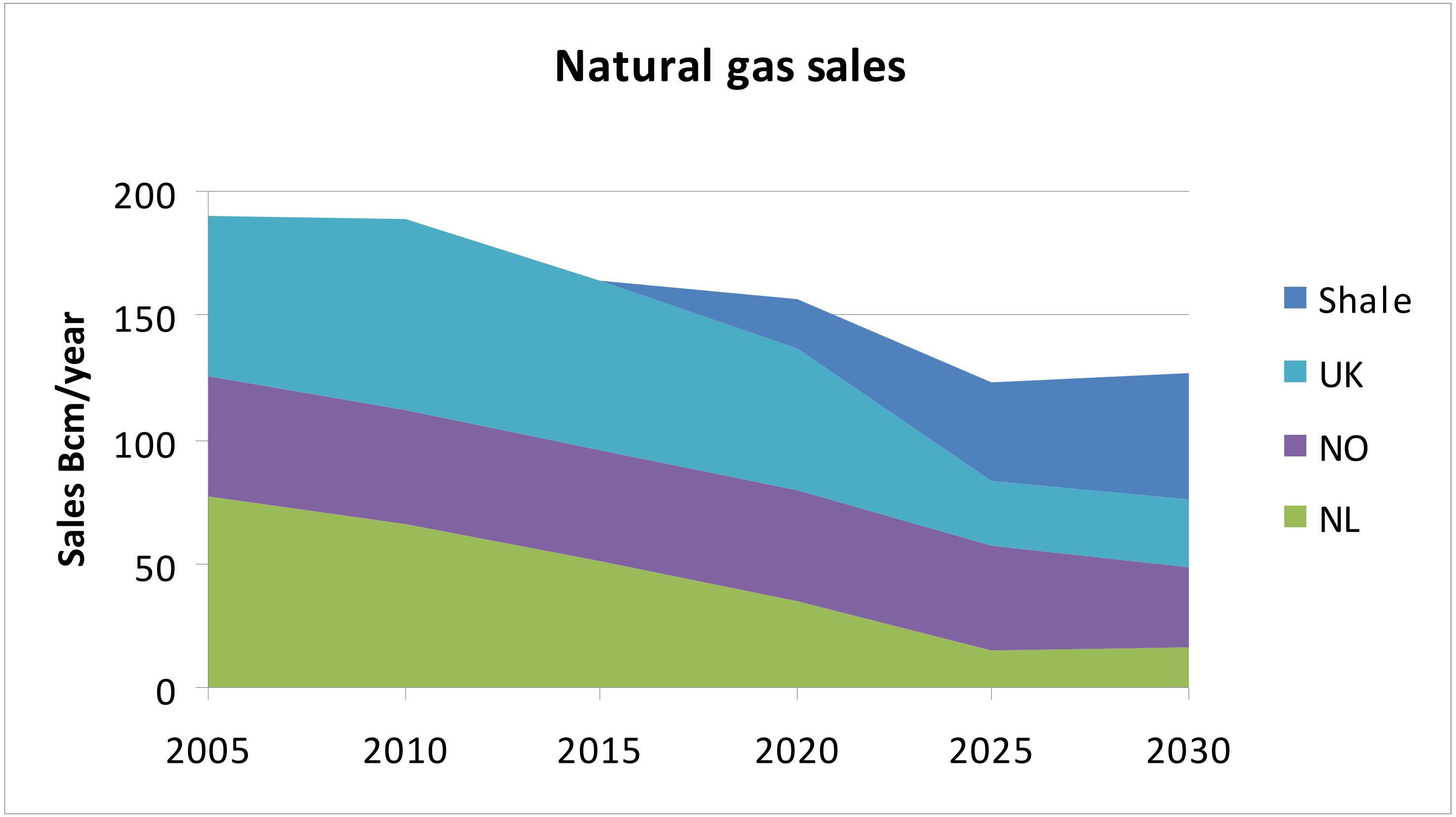
Price Error

9%

Shale gas in Europe

Case 0

Impact on the European production



Shale gas in Europe

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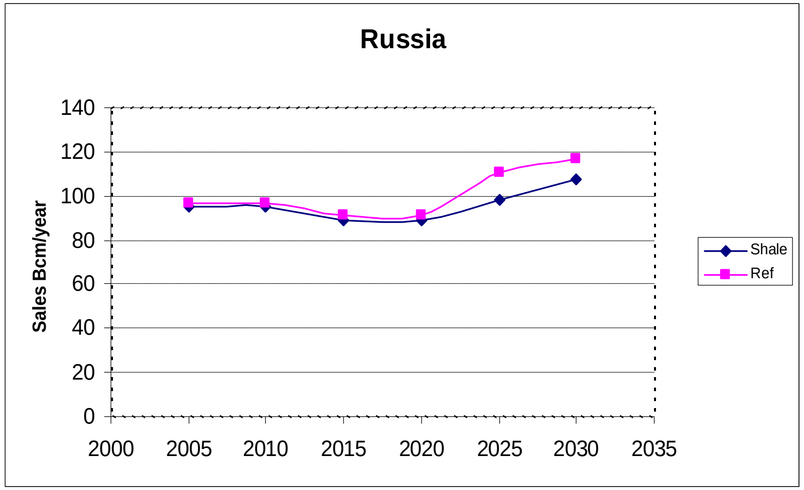

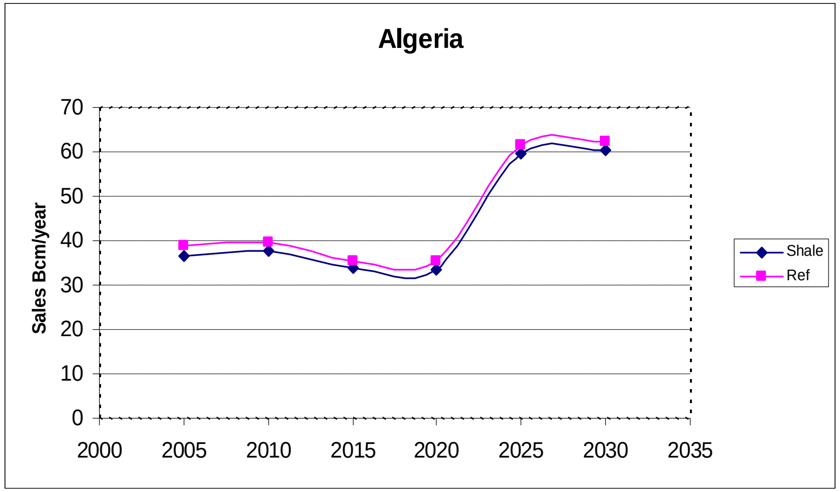

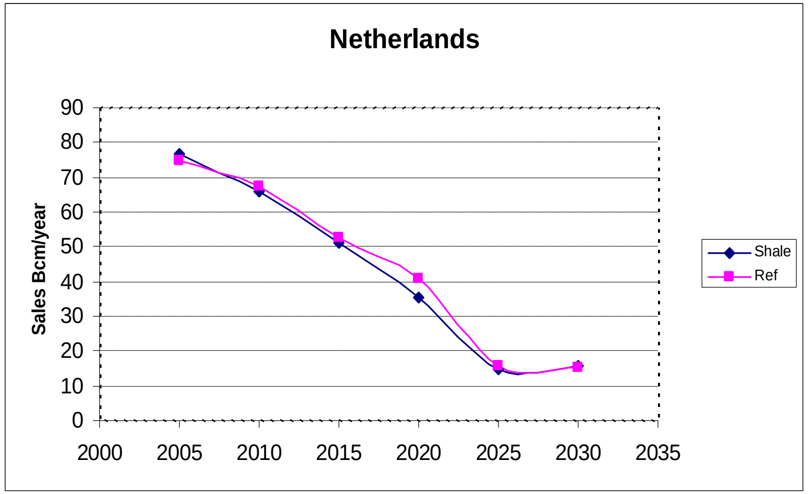

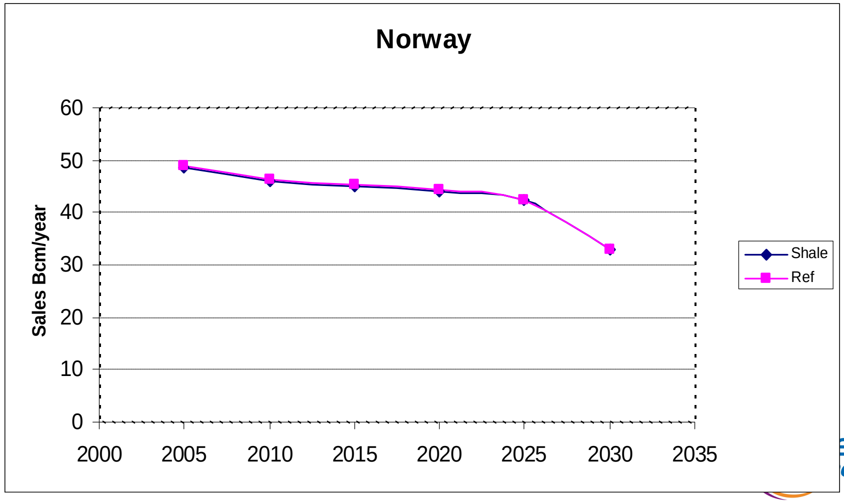

Shale gas in Europe

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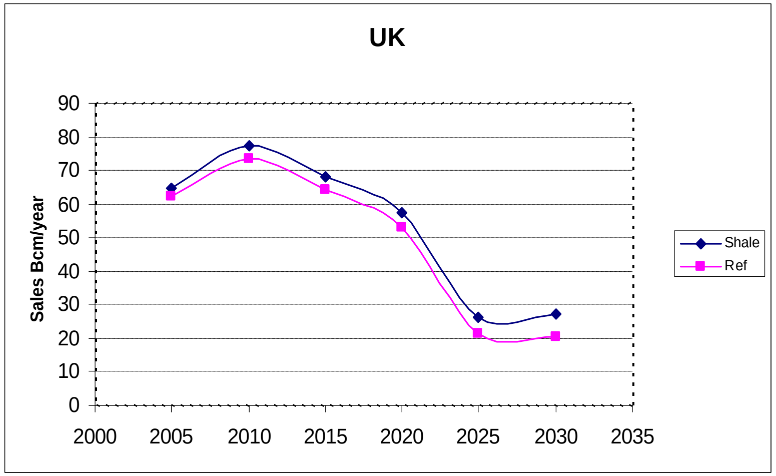

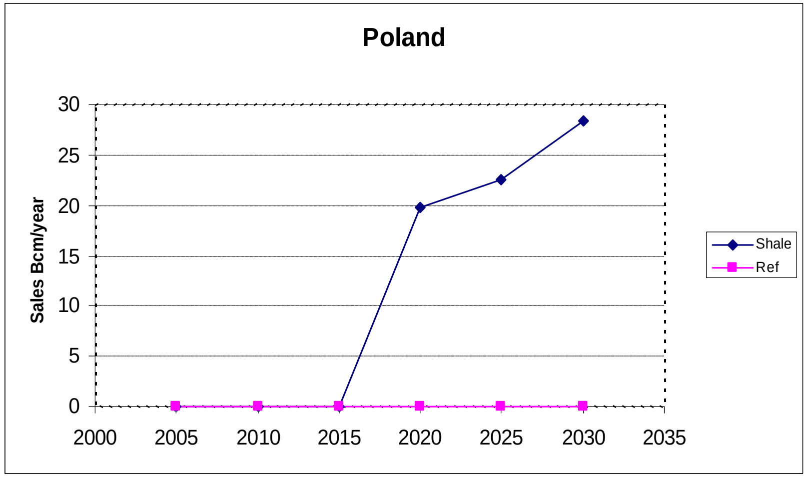

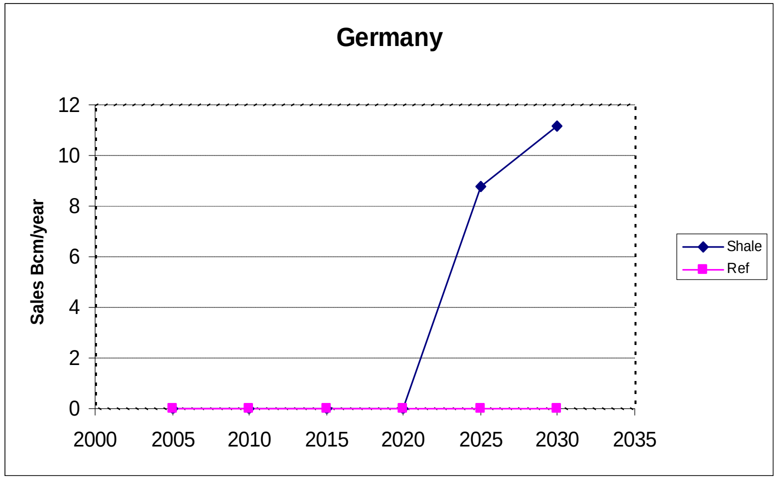

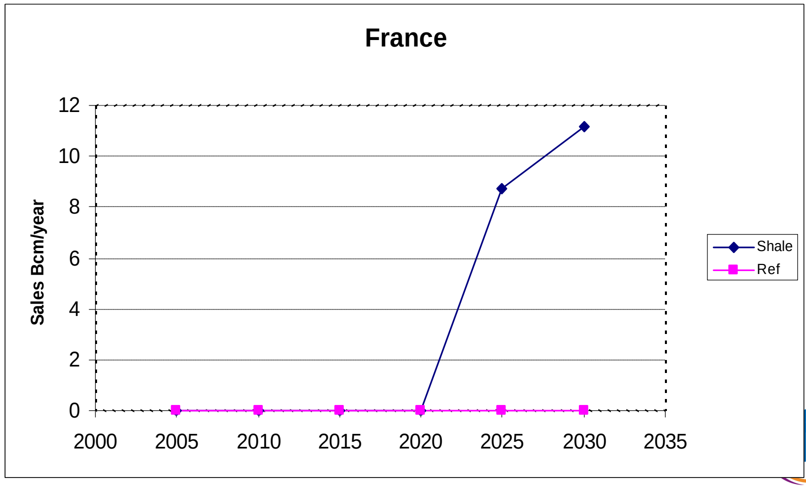

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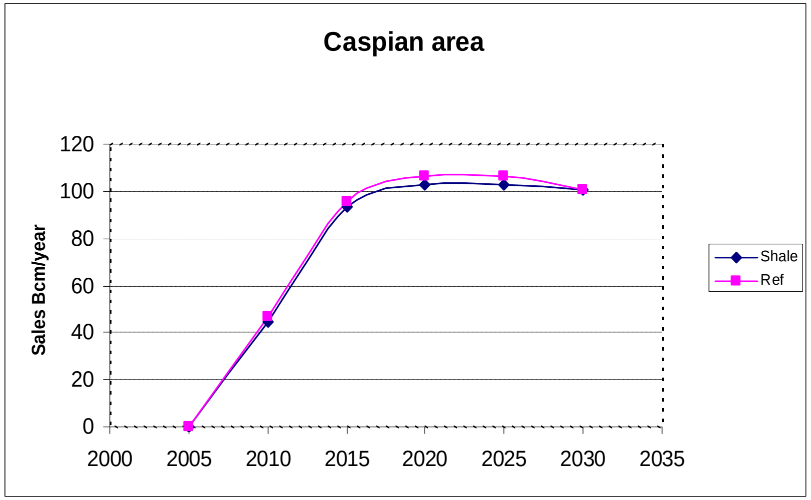

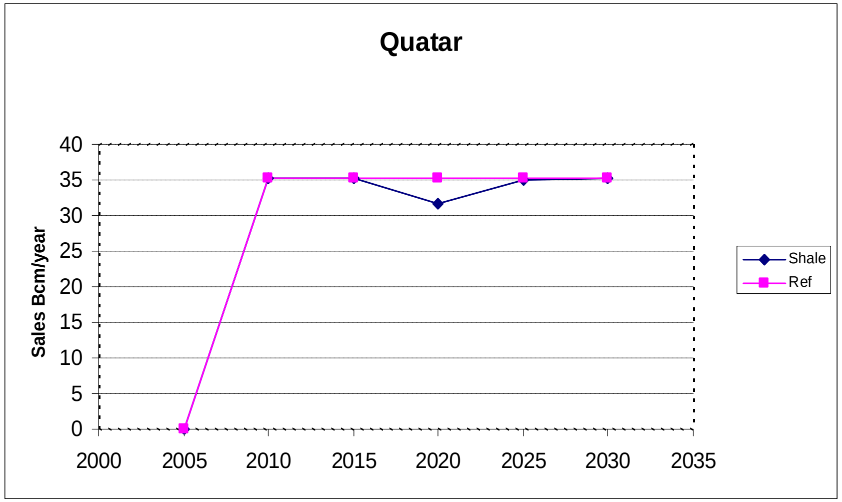

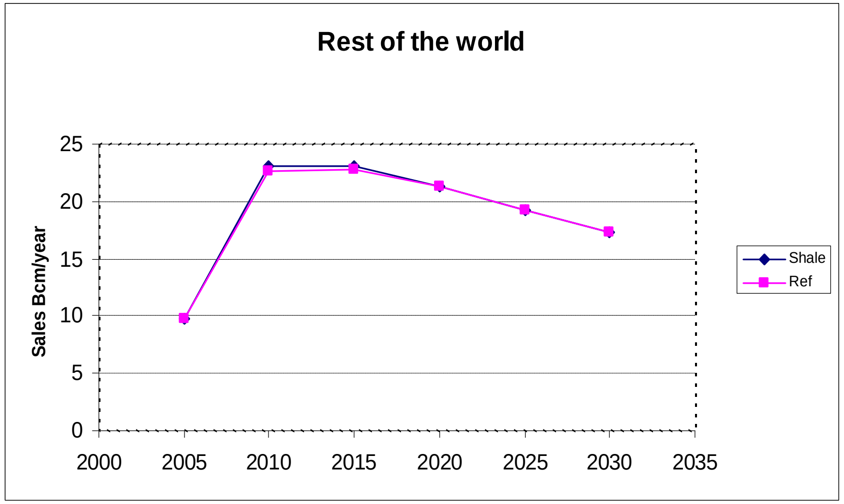

Shale gas in Europe

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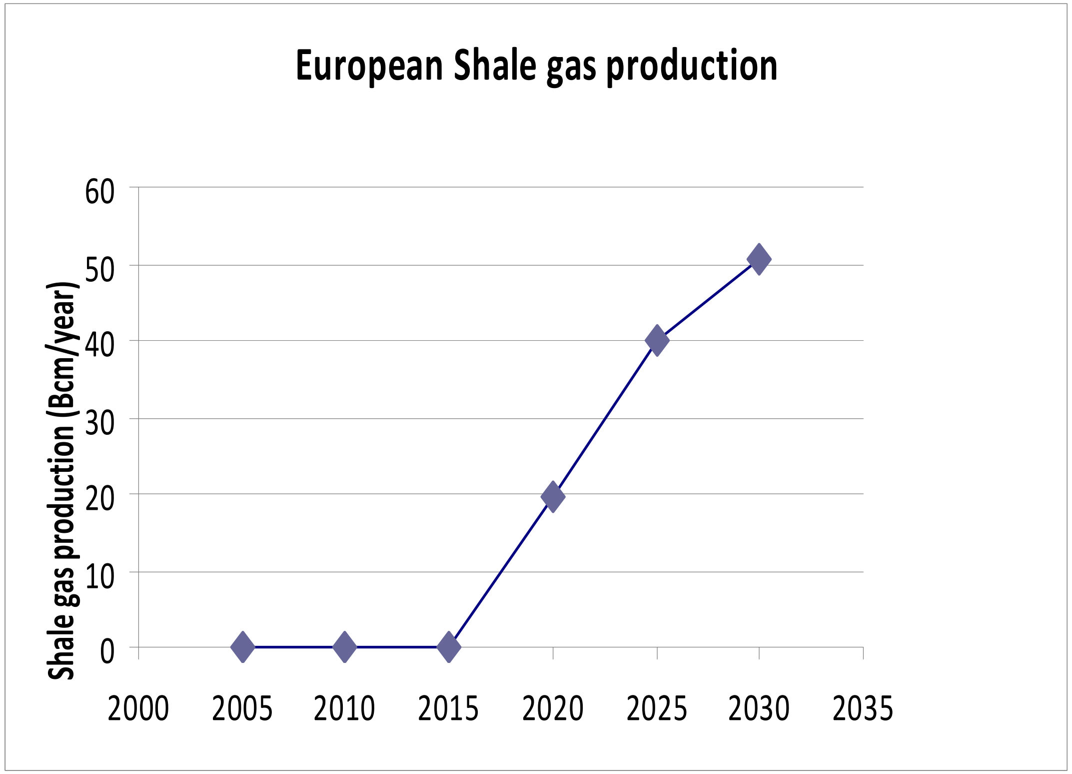
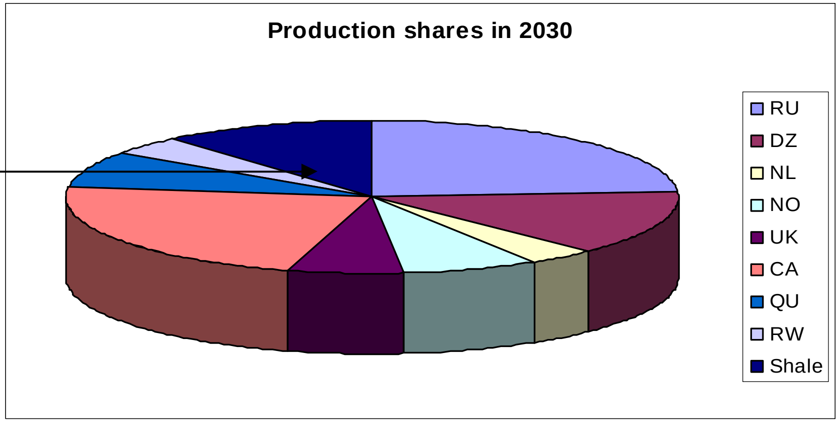


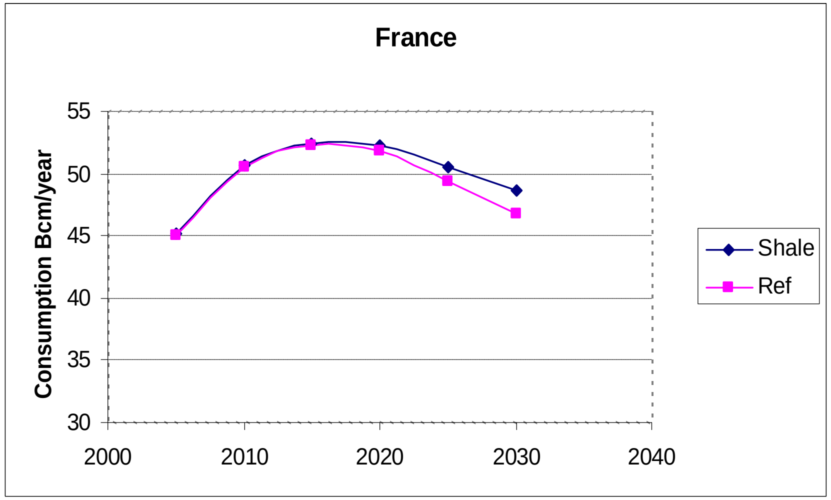


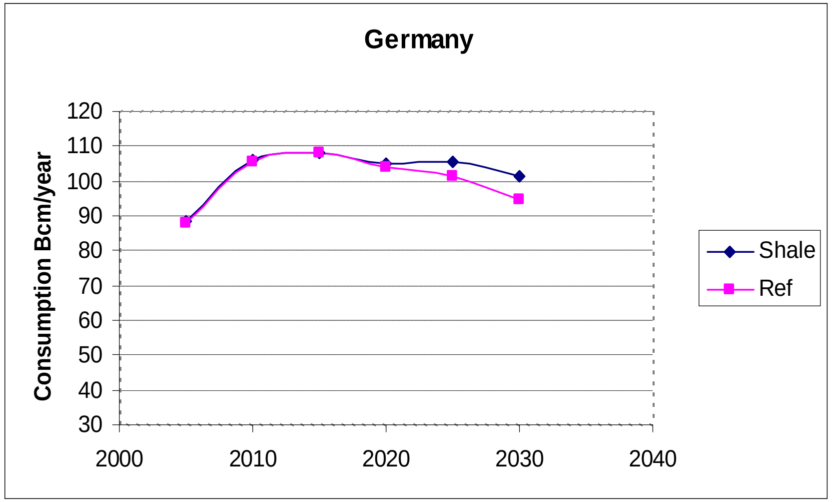
11% of shale gas in the production in 2030

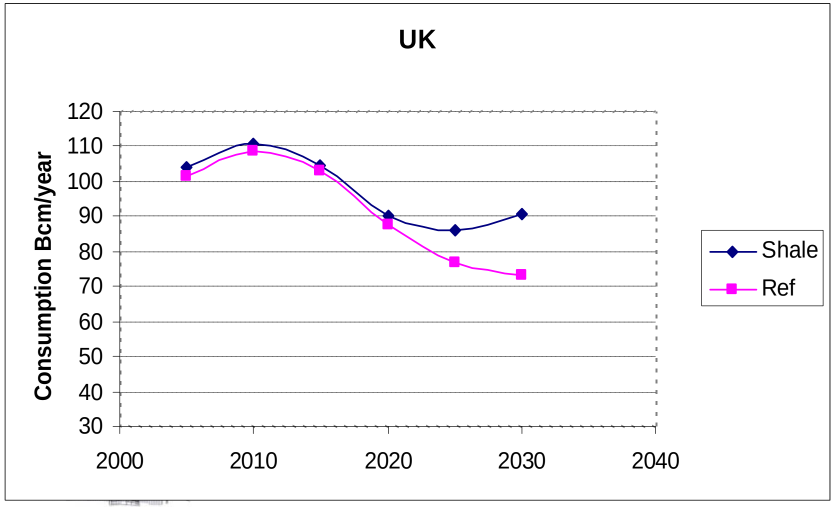
Shale gas in Europe

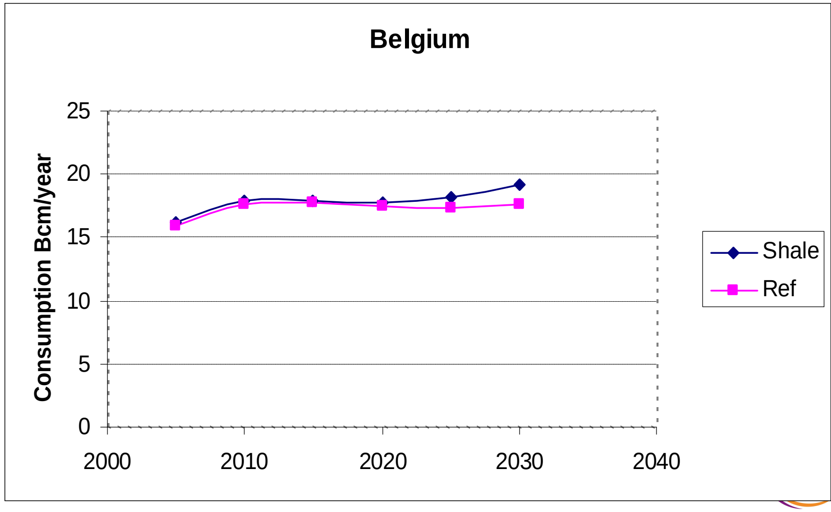
Case 0

Impact on the consumption





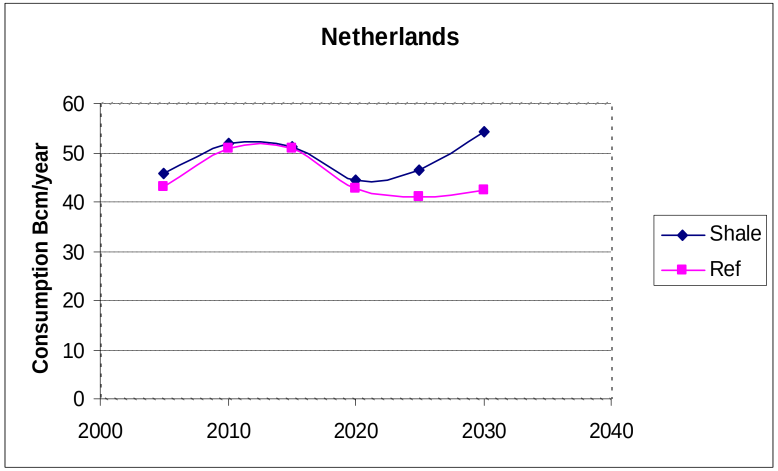


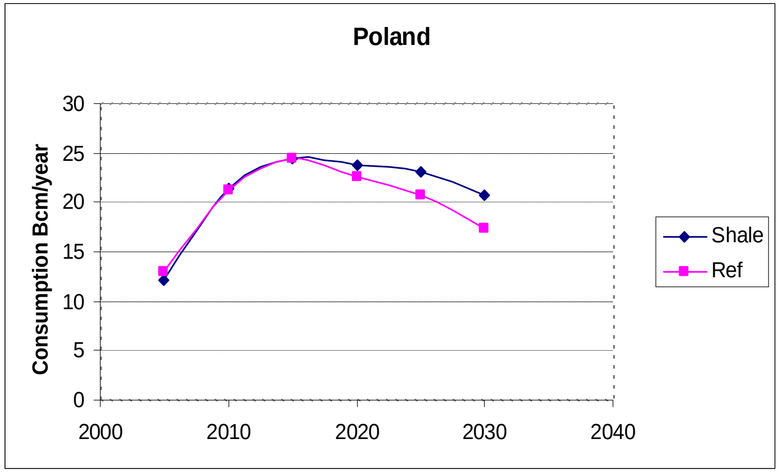


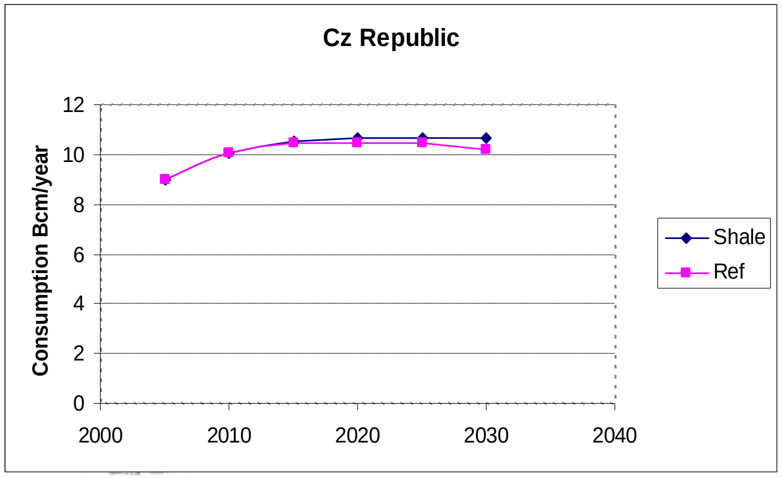
Shale gas in Europe

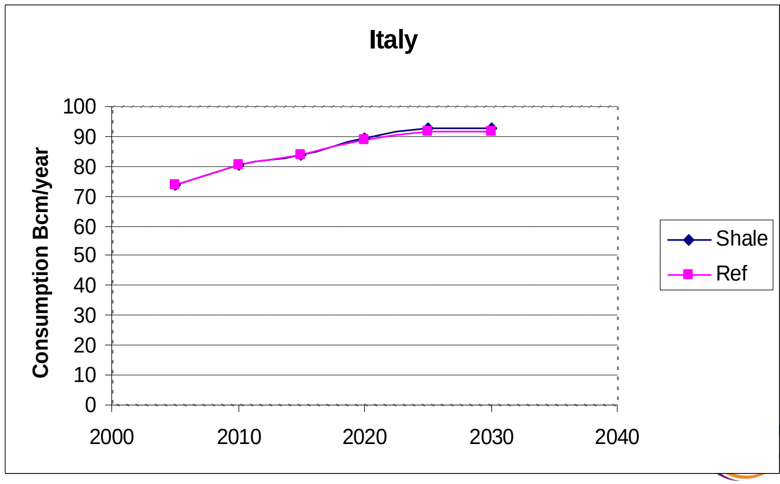
Case 0

Impact on the consumption









Energies
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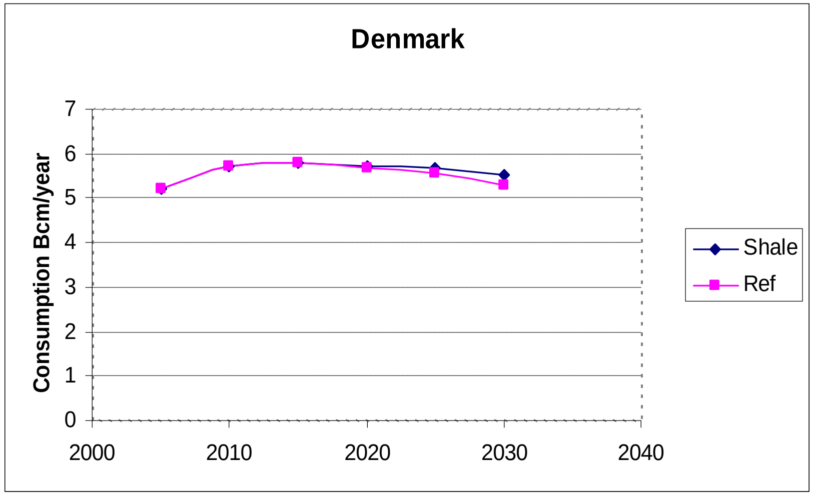
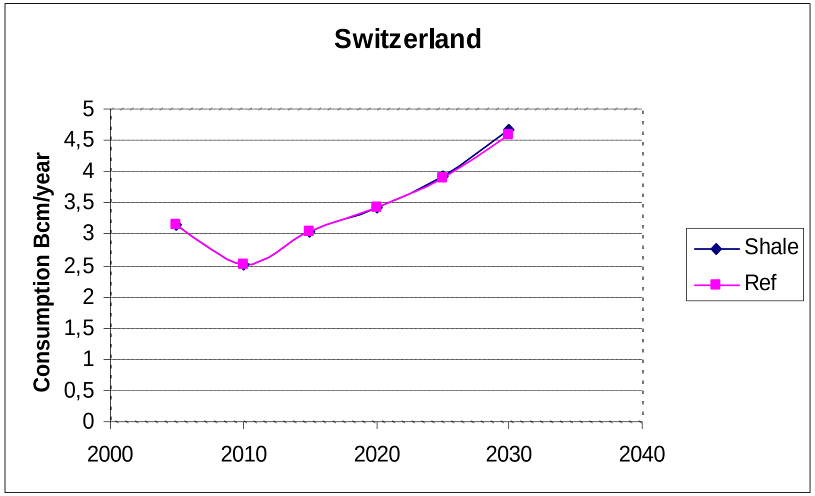
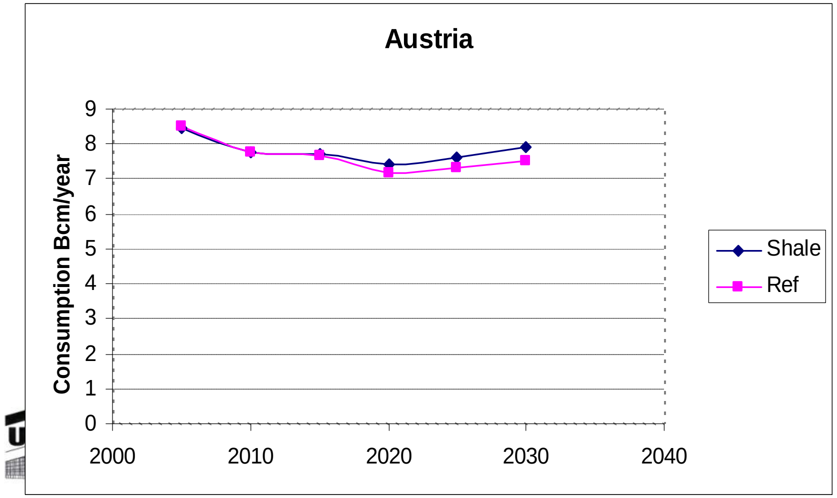
Shale gas in Europe

Case 0

Impact on the consumption



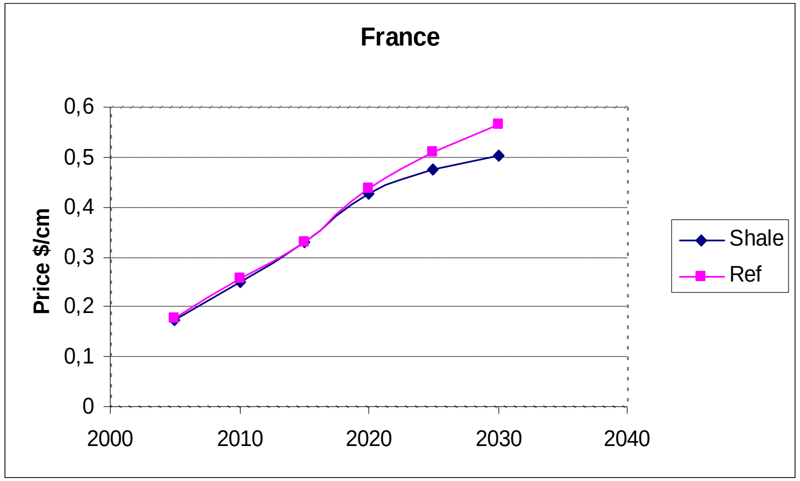


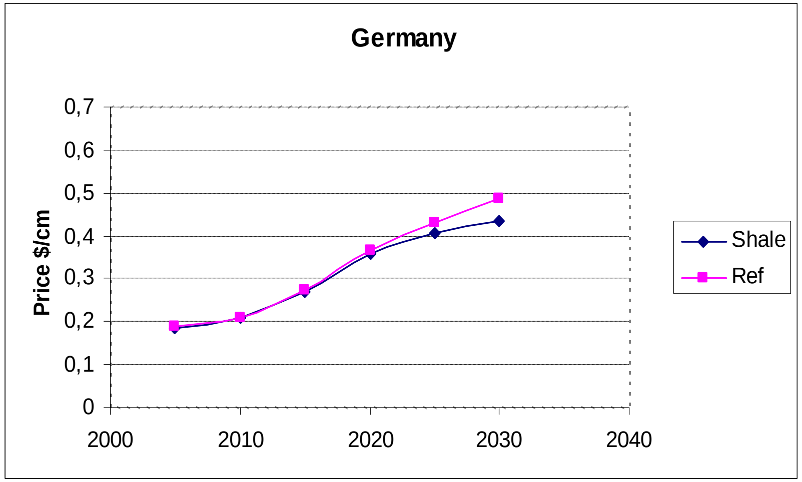


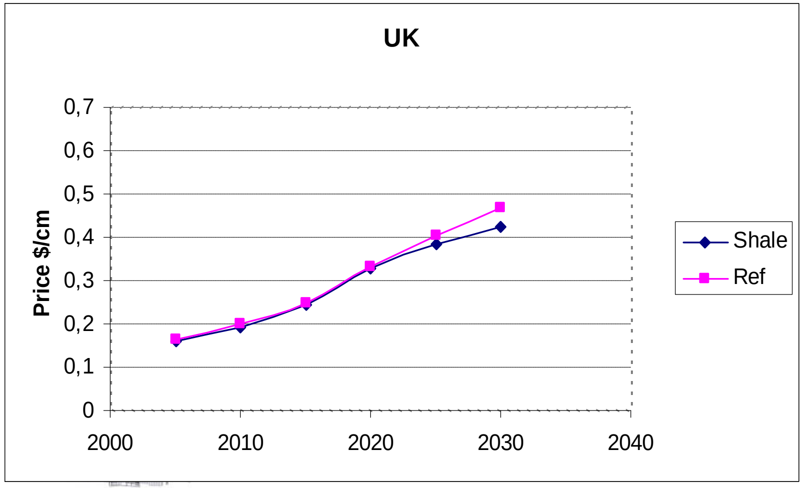
Shale gas in Europe

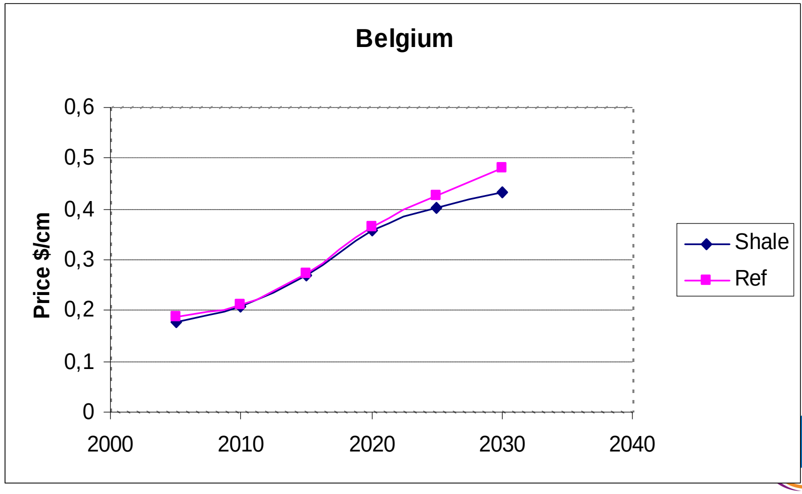
Case 0

Impact on the prices





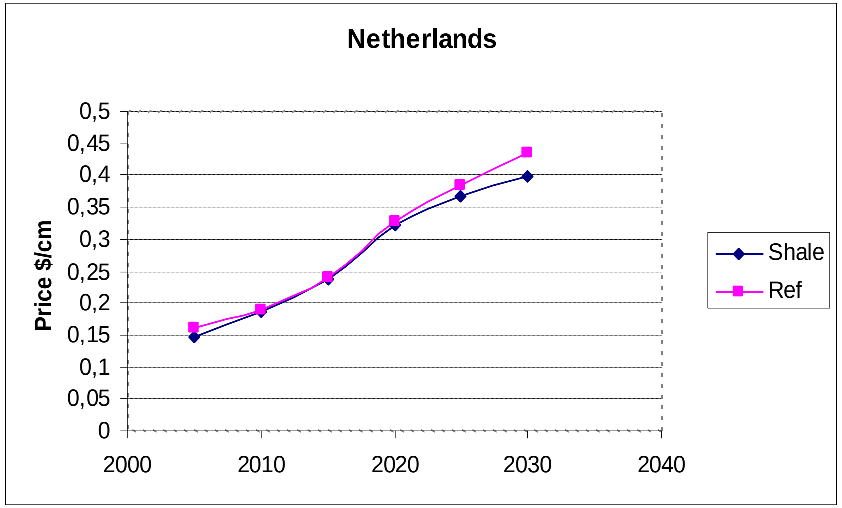


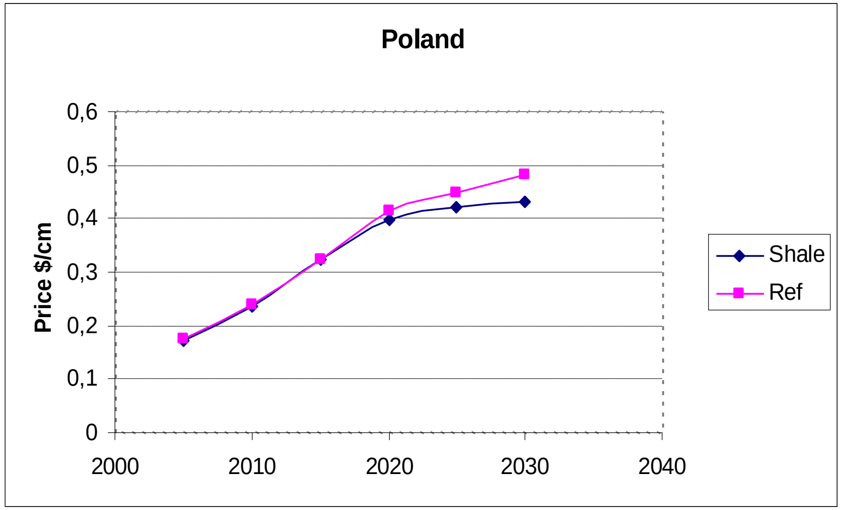


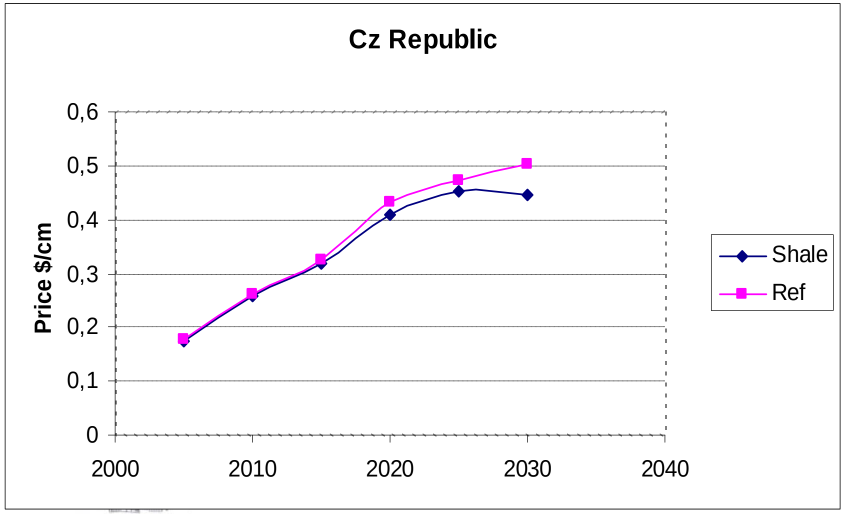
Shale gas in Europe

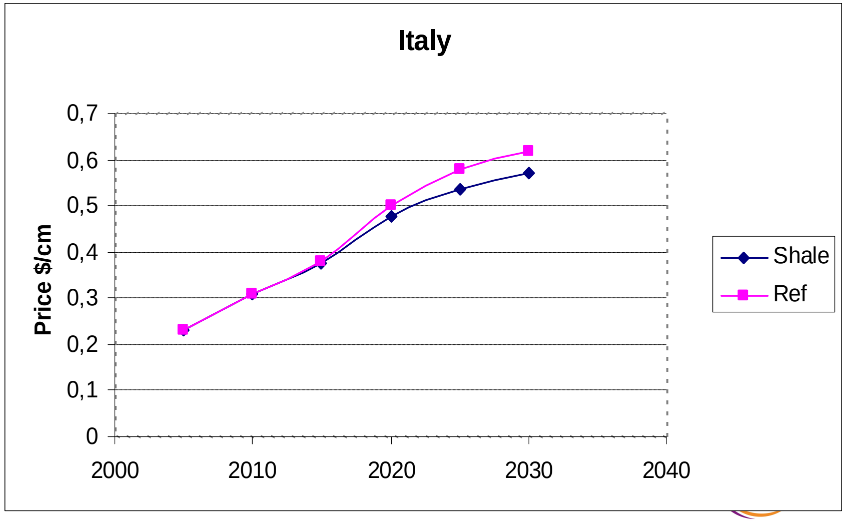
Case 0

Impact on the prices





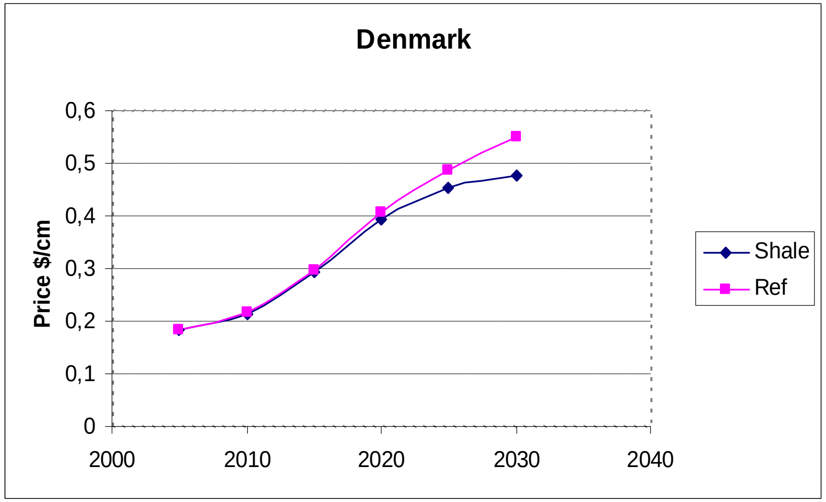


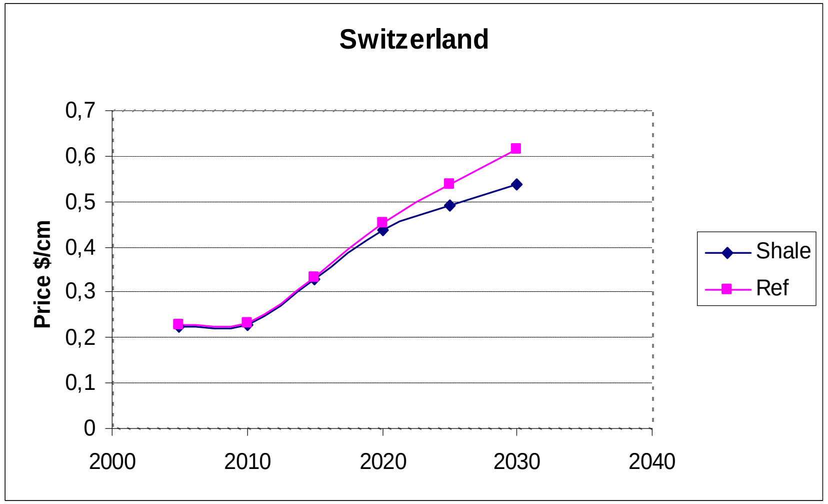


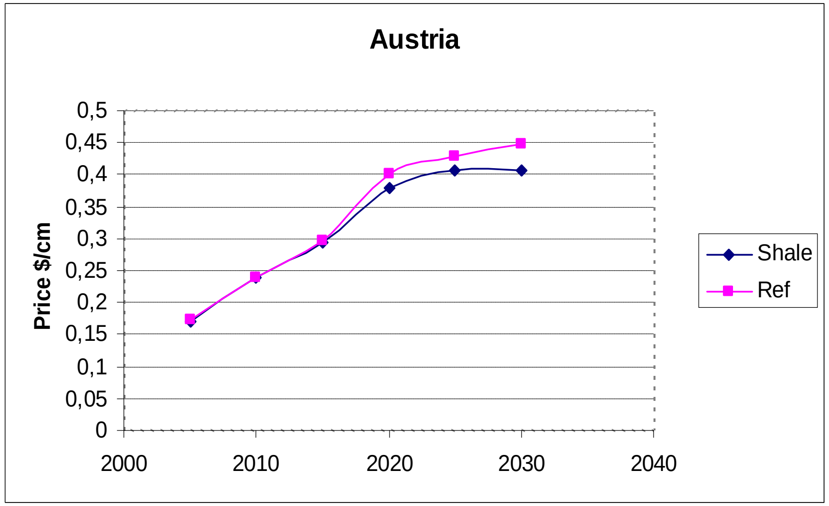
Shale gas in Europe

Case 0

Impact on the prices







Conclusions

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

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

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

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

ÅThe shale gas will reduce the Russian market share by 9%, principally because of Poland.

Thank you for your attentioné