Multi-objective bi-level optimization problem for the investment in new gas infrastructures
Context

Which infrastructures are key for the creation of a single European natural gas market?

The European Commission has banked on more investments in infrastructure to help EU countries to physically integrate their energy markets, enabling them to diversify their energy sources building a fully-integrated internal market → Projects of Common Interest (PCI)

ENTSOG Infrastructures priority

- Market Integration
- Security of supply
- Competition
- Sustainability

Assessment of the different investment options
The model: GASMOPEC

A multi-objective bi-level optimization model for representing the investment decision process in the European natural gas market

**Upper-Level Problem**

Investment decision making process: new pipeline and regasification capacity → Multiple criteria:

- Different optimal investment plans

EC acts as network planner

*optimizing investment decisions*

\[ f = \{p, q\} \]

**Lower-Level Problem**

Equilibrium Downstream Natural Gas Market

Natural gas market agents:

*Solve optimization problems with investment fixed* \( f = \{\text{prices, quantities}\} \)
The upper level

Several criteria that need to be taken into account simultaneously when taking investment decisions

Criteria:

- **Investment costs:** Pipeline & regasification capacity
- **Market integration:** Price convergence minimizing price differences among consumption nodes
- **Security of supply:** Maximizing diversity of suppliers
- **Competition:** Maximizing the utility of demand → lower gas supply costs and marginal prices

Depending on the importance assigned to each of these criteria, different optimal investment plans
The lower level

Nash-Cournot equilibrium structured as a two-stage-game

Transmission System Operator (TSO)
- Fixed cost + congestion fees

Cross-border pipeline

LNG Operator
- Fixed cost + congestion fees

Downstream
- Elastic demand

Demand

Liquefaction terminal

Transport

Regasification terminal

Upstream
- Fixed cost

Traders

Marketers
The lower level

The market structure:

**AGENT'S CHARACTERISTICS**
- Traders
- Marketers
- Demand
- Pipelines operator
- LNG operator

**SYSTEM CHARACTERISTICS**
Technical constraints
- Liquefaction terminals capacity
- Regasification terminals capacity
- Cross-border pipelines capacity
- Balancing zones (demand node)

**MARKET CHARACTERISTICS**
- Elastic demand
- Marketers-final demand: Nash-Cournot equilibrium

**EXPANSION CAPACITY**
(given from the upper level)
- Regasification terminals capacity
- Cross-border pipelines capacity

Downstream gas market
Methodological approach (I)

Mathematical Problem with Equilibrium Constraints (MPEC)

Upper level: *Multi-objective problem:*

- Solution: non-dominated solution set of optimal points (trade-off solutions).
- Decision space is discrete
- Scalarizing techniques: e-constraint technique

\[
\text{Max} \\
\text{Demand Utility} - \rho_1 \cdot \text{Total Cost} - \rho_2 \cdot \text{Price difference}_{zz_1} + \rho_2 \cdot \text{Number supply sources}
\]

\[
s.t. \\
\text{Total Cost} \leq e_1; \text{Price difference} \leq e_2; \text{Number supply sources} \geq e_4; \rho_i = 0.0001
\]
Methodological approach (II)

Mathematical Problem with Equilibrium Constraints (MPEC)

**Lower level:** *Market equilibrium problem*

- Karush-Kuhn-Tucker (KKT) optimality condition
- Problem is reformulated as a mixed-integer quadratic problem (MIQCP)

*Solved using*

GAMS

Gurobi
Case Study

North-South Gas Interconnections in **Western Europe**

- **Demand nodes**: Benelux (The Netherlands, Belgium and Luxemburg) (BE), France (FR), Germany (GE), Italy (IT), Spain (ES) and the United Kingdom (UK+Ireland).

- **Exporters** (i.e. traders): Russia (RU), Algeria (DZ), the European producers (Norway (NO) and the Netherlands (NE)) and Middle East (represented by Qatar (QT)).

- **2015 - 2035** (ten-year steps)

- **50 cases**: varying the upper and lower reservation levels
Case Study

Methods:

1. **Weighted method:**
   - No endogenous investment when assigning all the criteria the same importance.
   - Western Europe is well interconnected, and no investment is compensated in terms of utility of the demand.

2. **E-constraint method:**
   - E-constraint method problem: assigning reservation levels \( \rightarrow \) Reservation levels assigned running each criteria as objective function
   - The allowed investment (i.e. in pipeline and regasification capacity) is increased from case 1 to 50.
Case Study

Results cases 1 to 10:

- No investment allowed
- The maximum permitted price difference is increased while the requested minimum number of suppliers is diminished from cases 1 to 10
Case Study

Results cases 11 to 21:

- Some investment allowed

Investment in regasification capacity reduces gas prices at the consumption node
Case Study

Results cases 21 to 50:

- Increasing investment allowed

The investment in new pipeline capacity reduces price difference between zones but its impact in terms of utility of the demand is almost negligible.
Case Study

Converging prices is a sign of well integrated market... however in this case, it is at the expenses of reducing the utility of the demand.
Conclusions

We provide a novel tool for assisting the investment decision making process, analyzing the different investment options (i.e. in pipelines and regasification terminals).

- Bi-level model:
  - Natural sequence of investment and operation decisions
  - Different interest of market participants

- Multi-objective model:
  Evaluate different expansion plans under different criteria

Assessment optimal infrastructure investment Western Europe:
- Western Europe is well interconnected; second,
- The investment in two regasification terminals (i.e. in France and the United Kingdom) enhance the utility of the demand
- Pipeline capacity with incumbent major gas suppliers (i.e. Algeria and Russia) increases.
Questions?

감사합니다

Natick

Đanke

Ευχαριστίες

Köszönöm

感激

Tack

Gracias

Merci

お礼

TEŞEKKÜR EDERİM
The upper level

**Investment costs**

\[ \text{Minimize } (f_1) = \text{Min } \{ \text{cost}_{\text{invpipe}} + \text{cost}_{\text{invreg}} \} \]

s.t. maximum capacity expansion constraint

**Market integration**

\[ \text{Minimize}(f_2) = \text{Min} \left\{ \sum_{zz_1p/\{z,z_1 \in K^CN_z\}} (\Delta p_{zz_1p}) \right\} \]

s.t. \[ \Delta p_{zz_1p} \geq p_{zp} - p_{z_1p} \quad \forall \ z, z_1, p/\{z, z_1 \in K^CN_z\} \]
\[ \Delta p_{zz_1p} \geq p_{z_1p} - p_{zp} \quad \forall \ z, z_1, p/\{z, z_1 \in K^CN_z\} \]

**Utility of demand**

\[ \text{Maximize}(f_3) = \text{Max} \left\{ \int_0^{Q_{z_1p}} p_{z_1p}(q_{z_1p}) \cdot dq_{z_1p} \right\} \]

s.t. \[ p_{z_1p} = P_{z_1p}^0 - \alpha_{z_1p} \cdot \sum_{m,z} (q_{mzz_1p}^{mak}) \quad \forall \ z_1, p \]
The upper level

Sources of supply

Maximize \( f_4 = \max \left\{ \sum_{zz_1p/\{z\in K^T_z\} \cap \{z \neq z_1\} \cap \{z_1 \in K^M_{z_1}\}} (\delta^{t_{NG}}_{zz_1p} + \delta^{t_{LNG}}_{zz_1p}) \right\} \)

s.t.  
\[
\delta^{t_{NG}}_{zz_1p} = 1 \iff \sum_{t \in z} q^{t_{NG}}_{tzz_1p} \geq b; \quad \delta^{t_{NG}}_{zz_1p} = 0 \iff \sum_{t \in z} q^{t_{NG}}_{tzz_1p} \leq b
\]

\[
\sum_{t \in z} q^{t_{NG}}_{tzz_1p} - b + \varepsilon \leq \delta^{t_{NG}}_{zz_1p} \cdot (Q^{pipe}_{zz_1p} + CAP^{invpipe}_{pzz_1}) \quad \forall z, z_1, p
\]

\[
\sum_{t \in z} q^{t_{NG}}_{tzz_1p} - b \geq (1 - \delta^{t_{NG}}_{zz_1p}) \cdot (-b) \quad \forall z, z_1, p
\]

\[
\delta^{t_{LNG}}_{zz_1p} = 1 \iff \sum_{t \in z} q^{t_{LNG}}_{tzz_1p} \geq b; \quad \delta^{t_{LNG}}_{zz_1p} = 0 \iff \sum_{t \in z} q^{t_{LNG}}_{tzz_1p} \leq b
\]

\[
\sum_{t \in z} q^{t_{LNG}}_{tzz_1p} - b + \varepsilon \leq \delta^{t_{LNG}}_{zz_1p} \cdot (Q^{reg}_{z_1p} + CAP^{invreg}_{z_1p}) \quad \forall z, z_1, p
\]

\[
\sum_{t \in z} q^{t_{LNG}}_{tzz_1p} - b \geq (1 - \delta^{t_{LNG}}_{zz_1p}) \cdot (-b) \quad \forall z, z_1, p
\]
The lower level

**Traders**

\[
\text{Max} \quad \Pi_{tzz_1p}^{\text{trader}}
\]
\[
= b_{pz_1p} \cdot (q_{tNZ}^{tNG} + q_{tzz_1p}^{tLN}) - C_{tp} \cdot (q_{tzz_1p}^{tNG} + q_{tzz_1p}^{tLN})
- \sum_{(z,z_1)\in K_{tzz_1p}^{\text{trader}}} (\text{cost}_{zz_1}^{\text{pipe}} \cdot q_{tzz_1p}^{tpipe}) - \sum_{(z,z_1)\in K_{tzz_1p}^{\text{trader}}} (\text{cost}_{zz_1}^{\text{ship}} \cdot q_{tzz_1p}^{tship}) \quad \forall \ t, z, z_1, p
\]

s.t.

**Available gas for sale:**

\[
\sum_{t,z_1} q_{tzz_1p}^{tNG} + \sum_{t,z_1} q_{tzz_1p}^{tLN} \leq Q_{tp}^{\text{tra}} : (\lambda_{z_1p}^{\text{tra}}) \quad \forall \ z, p
\]

**Flow conservation constraint:**

\[
\begin{bmatrix}
\sum_{z_1 \neq z} q_{tzz_1p}^{tNG} \quad - \quad \sum_{z_1 \neq z} q_{tzz_1p}^{tpipe}
\end{bmatrix}
+ \begin{bmatrix}
\sum_{z_1 \neq z} q_{tz_1zp}^{tpipe} \quad - \quad \sum_{z_1 \neq z} q_{tzz_1p}^{tNG}
\end{bmatrix}
= 0 : (\phi_{tzp}^{tpipe}) \quad \forall \ t, z, p
\]

\[
\begin{bmatrix}
\sum_{z_1 \neq z} q_{tzz_1p}^{tLN} \quad - \quad \sum_{z_1 \neq z} q_{tzz_1p}^{tship}
\end{bmatrix}
+ \begin{bmatrix}
\sum_{z_1 \neq z} q_{tz_1zp}^{tship} \quad - \quad \sum_{z_1 \neq z} q_{tzz_1p}^{tLN}
\end{bmatrix}
= 0 : (\phi_{tzp}^{tship}) \quad \forall \ t, z, p
\]
The lower level

**Upstream market clearing condition:** traders - marketers

\[ \sum_{t,z} q_{tzz_1p}^{tNG} + \sum_{t,z} q_{tzz_1p}^{tLNG} = \sum_{m,z} q_{mzz_1p}^{mak} : (bp_{zp}) \ \forall \ z_1, p \]

**Marketers**

Max \[ \Pi_{mzz_1p}^{marketer} \]

\[ = p_{z_1p} \cdot (q_{mzz_1p}^{mak}) - bp_{zp} \cdot (q_{mzz_1p}^{mak}) - \sum_{(z,z_1) \in K_{mzz_1}^{marketer}} (cost_{zz_1}^{pipe} \cdot q_{mzz_1p}^{pipe}) \ \forall \ m, z, z_1, p \]

s.t. flow conservation constraint:

\[ \left[ \sum_{z_1 \neq z} q_{mzz_1p}^{mak} - \sum_{z_1 \neq z} q_{mzz_1p}^{mzpipe} \right] + \left[ \sum_{z_1 \neq z} q_{mzz_1p}^{mzpipe} - \sum_{z_1 \neq z} q_{mzz_1zp}^{mak} \right] = 0 : (\phi_{mzp}^{mak}) \ \forall \ m, z, p \]

**Downstream market clearing condition:** marketers - demand

\[ p_{z_1p} = p_{z_1p}^{0} - \alpha_{z_1p} \cdot \sum_{m,z} (q_{mzz_1p}^{mak}) \ \forall \ z_1, p \]
The lower level

System Operator

\[
\text{Max}_{q_{zz1p}} \Pi_{zz1p}^{\text{pipe}} = \text{cost}_{zz1}^{\text{pipe}} \cdot (q_{zz1p}^{\text{totalpipe}}) - TC_{zz1}^{\text{pipe}} \cdot (q_{zz1p}^{\text{totalpipe}}) \forall z, z_1, p
\]

s.t. Maximum capacity constraint:

\[
q_{zz1p}^{\text{totalpipe}} \leq Q_{zz1p}^{\text{pipe}} + \sum_{p_1/p_1<p} i_{p1zz1}^{\text{pipe}} : (\lambda_{zz1p}^{\text{pipe}}) \forall z, z_1, p
\]

Traders & marketers flows:

\[
q_{zz1p}^{\text{totalpipe}} = \sum_{m/(z,z1) \in K_{mzz1}^{\text{marketer}}} (q_{mzz1p}^{\text{pipe}}) + \sum_{t/(z,z1) \in K_{tzz1}^{\text{trader}}} (q_{tzz1zp}^{\text{pipe}}) : (\text{cost}_{zz1}^{\text{pipe}}) \forall z, z_1, p
\]
The lower level

**LNG Operator**

Maximize \( \prod_{zz_1p}^{\text{ship}} \) \( \Pi_{zz_1p}^{\text{ship}} = \text{cost}_{zz_1}^{\text{ship}} \cdot (q_{zz_1p})^{\text{totalship}} - TC_{zz_1}^{\text{ship}} \cdot (q_{zz_1p})^{\text{totalship}} \) \( \forall z, z_1, p \)

s.t. Maximum capacity constraint:

\[
\sum_{z_1} q_{zz_1p}^{\text{totalship}} \leq \bar{Q}_{zp}^{\text{liq}} : (\lambda_{zp}^{\text{liq}}) \quad \forall z, p
\]

\[
\sum_{z} q_{zz_1p}^{\text{totalship}} \leq \bar{Q}_{z1p}^{\text{reg}} + \sum_{p_1/p_1<p} i_{p_1zz_1}^{\text{reg}} : (\lambda_{z1p}^{\text{reg}}) \quad \forall z, z_1, p
\]

**Traders flows:**

\[
q_{zz_1p}^{\text{totalship}} = \sum_{t/(z, z_1) \in K_{tzz_1}^{\text{trader}}} (q_{tzz_1z_1}^{\text{ship}}) : (cost_{zz_1}^{\text{ship}}) \quad \forall z, z_1, p
\]