Energy Strategy Reviews 30 (2020) 100492

Contents lists available at ScienceDirect

Energy Strategy Reviews

journal homepage: http://www.elsevier.com/locate/esr

Multi-objective bi-level optimization model for the investment in gas infrastructures

Aurora del Valle *, Sonja Wogrin, Javier Reneses

Instituto de Investigación Tecnológica, Universidad Pontificia Comillas, C/Alberto Aguilera 23, 28015, Madrid, Spain

ARTICLE INFO

Keywords:
Natural gas market
Multi-objective bi-level optimization problem
Infrastructure investment

ABSTRACT

We propose a multi-objective bi-level optimization model for analyzing the different investment options (in natural gas pipelines and regasification terminals) within the EU framework under a market perspective, considering the different interest of market participants and the multiple criteria that need to be achieved simultaneously (i.e. market integration, security of supply and competition). The model consists of the objectives of the network planner at the upper level optimizing a multi-objective function and a lower level that represents the downstream European gas market. The model is used for the assessment of the optimal infrastructure investment in the North-South Gas Interconnections in Western Europe.

1. Introduction

The European Union (EU) has a set of energy targets and energy policy objectives in order to help the EU achieve a more competitive, secure and sustainable energy system. All the strategies put energy infrastructures at the forefront for the creation of a pan-European energy market and highlight the role of natural gas as a transitional fuel in a Climate and Energy framework. Additionally, in the Third Energy Package the EU legislation on the completion of the internal gas market, the facilitation of cross-border gas trade, the promotion of cross-border collaboration and the investment among the EU countries are addressed. Within this framework, the European Commission (EC) has banked on more investments in infrastructure to help EU countries to physically integrate their energy markets, enabling them to diversify their energy sources. In October 2013, the EC presented a list of energy infrastructure projects (i.e. electricity, gas and oil) that are of common interest (Projects of Common Interest – PCIs) and are considered as key in order to help the EU achieve its energy policy and climate objectives. The requirements that projects need to fulfill to become a PCI are: first, to have a heavy impact on market integration in at least two EU countries; second, to boost competition on energy markets; third, to enhance security of supply, and fourth, to add to the EU's climate and energy goals by integrating renewables.

The Regulation (EU) 347/2013,[1] gather up the previous requirements in the following four main criteria: market integration, security of supply, competition and sustainability. In line with these criteria, the indicators considered for the assessment of projects impact in the ENTSOG CBA Methodology [1] are: **market integration**, in terms of market access diversification, price convergence and balance in bi-directional capacity; **security of supply**, in terms of resilience in case of disruption, the level of disrupted demand, remaining flexibility and number of sources a country can access to; **competition,** in terms of number of gas sources, physical dependence on a single supply source, gas supply costs and marginal prices; and **sustainability**, in terms of CO_2 emissions.

At the present time, in the context of uncertainty, global relations and liberalized energy markets, the assessment of projects impact and consequently the decision-making process of Governments and regulators has been complicated immensely. For this purpose, the aim of the GASMOPEC model proposed in this paper is to provide a tool for assisting the investment decision making process to determine European Commission support, analyzing the different investment options in natural gas infrastructures within the EU framework under a market perspective. We propose a multi-objective bi-level optimization model which consists of the multiple objectives of the network planner at the upper level and a lower level that represents the downstream European gas market.

In the case study, the model is used for the assessment of the optimal

* Corresponding author.
E-mail addresses: au.delvalle@gmail.com (A. Valle), sonja.wogrin@comillas.edu (S. Wogrin), javierr@comillas.edu (J. Reneses).

[1] Regulation (EU) No 347/2013 of the European Parliament and of the Council of 17 April 2013 on guidelines for *trans*-European energy infrastructure and repealing Decision No 1364/2006/EC and amending Regulations (EC) No 713/2009, (EC) No 714/2009 and (EC).

https://doi.org/10.1016/j.esr.2020.100492
Received 9 July 2018; Received in revised form 13 February 2020; Accepted 8 May 2020
Available online 7 June 2020

infrastructure investment in the North-South Gas Interconnections in Western Europe (NSI West Gas) under a market price perspective. NSI West Gas aims to facilitate the transport of gas between Northern and Southern Europe, diversifying supply sources and increasing the availability of gas and involves the following countries: Belgium, France, Germany, Ireland, Italy, Luxemburg, Malta, The Netherlands, Portugal, Spain, and the United Kingdom.

The remainder of this paper is organized as follows. Section II includes the state of the art, Section III presents the proposed bi-level model, Section IV provides some results from the case study, analyzing the optimal infrastructure investment in Western Europe. Results are analyzed and discussed in detail. Finally, Section V provides some relevant conclusions.

2. Literature review

Models whose objective is to represent the operation and investment decisions of natural gas markets abound in the literature. Some large-scale operations and investment natural gas models focus on a deterministic cost minimization approach such as The Natural Gas Transmission and Distribution Module (NGTDM), which is the module that represents the natural gas market of the multi-sector model **National Energy Modeling System (NEMS)** [2,3], developed and used by the U. S. Department of Energy. Another example is the family of models developed by EWI Cologne, **EUGAS** [4], **MAGELAN** [5] and **TIGER** [6–9]. All of them have a detailed infrastructure description assuming perfect competitive players. EUGAS models natural gas market operation and investment decisions and the TIGER model is used to analyze potential investments in gas transportation capacities based on congestion rents and nodal prices. The **RAMONA** model [10] formulates the investment problem as mixed-integer quadratic problem, assuming that investment decisions are semi-continuous and adding pressure flow relationships as well as the gas quality. Its stochastic version is presented in Refs. [11]. The **European Gas Market Model (EGMM)** [12] is a competitive short-run equilibrium model for the natural gas market in Europe developed by the Regional Centre for Energy Policy Research (REKK) used for the evaluation of natural gas infrastructure projects contrasting equilibrium outcomes with and without the investments.

However, due to the liberalization of gas markets, the investment and operation decisions have become a more complex problem and agents' interests are no longer driven by a mere cost minimization. Therefore, in order to represent the opportunities in a still imperfect gas market, a profit maximization approach is more suitable. The most commonly used approach for representing the effects of strategic behavior of market agents in the natural gas sector is game theory, which is the technique used in this paper.

In a first application [13,14], analyze the market power in the European natural gas sector and [15,16] analyze the effects of the gas market liberalization. Since then, several equilibrium models for representing the natural gas market have been developed. The most relevant ones are cited below, with special focus on the ones that endogenously represent both infrastructures capacity expansion and market operation. The **GASTALE** model [17–19], **NATGAS** model [20] and **GASMOD** model [21] are game theory equilibrium models of the European natural gas market describing the behavior of gas producers, transmission system operators (TSO), storage system operators (SSO), traders and consumers, and simulating the investment decision-making for additional gas infrastructures i.e. pipelines, LNG (liquefied natural gas) capacity, as well as storage (GASMOD allows endogenous capacity expansions only in new pipeline capacity). The stochastic version of GASTALE [22] analyzes investments in the natural gas sector considering uncertainty. The **World Gas Model (WGM)** [23–25] and its stochastic version [26] and the **Global Gas Model (GGM)** [27,28] and its stochastic version S-GGM [29], are complementarity models for the global natural gas market which allow for endogenous investments in pipelines and storage capacities, as well as for expansion on regasification and liquefaction capacities worldwide. Other works include [30], that provides an in-depth discussion of the existing models.

The principal advantage of market equilibrium models, modeling investment and operation decisions, is to represent the pipeline network and the access to other infrastructures as regasification terminals or storage under an imperfect competition framework, allowing to simulate the interaction between market power, capacity hoarding, infrastructure bottlenecks and their impact on optimal capacity expansion.

However, all of them simplify the dynamic nature of the operation and investment problem, as expansion and operation decisions are assumed to be taken simultaneously while, in reality, expansion and operation decisions are taken sequentially. The approach that allows to model this type of two-level structure of the investment problem, is referred to as Bi-level Programming Problems (BPPs) and were introduced in the early 1970s by Bracken and McGill in Refs. [31–33]. Among the existing bi-level approaches we opt for Mathematical Programs with Equilibrium Constraints (MPECs) [34]. Even these types of models have been extensively used in the electricity sector in the expansion capacity framework, the literature related to bi-level models is still scarce in natural gas markets. Some examples of bi-level optimization problems in the gas sector are [35], who developed a stochastic two-stage game for the European Gas Market with Norway as the leader; [36], who present a mixed integer bi-level linear programming model in order to analyze shippers' imbalances for reducing the penalties associated to those imbalances; and [37], who propose a new methodology for solving MPECs and applied it to a gas market model. Additionally, in Ref. [38] the total production costs of natural gas and electricity are minimized solving a bi-level problem where the upper level is an economic dispatch optimization model for the electricity system, while the lower level is an optimal allocation problem for natural gas system.

Therefore, the contribution of this paper is to cover the gap found in the literature regarding bi-level optimization models applied to investment in natural gas markets. This contribution is hence three-fold:

1) We introduce the natural sequence of investment and operation decisions into a gas market model (note that the sequentiality has an impact on results)
2) By making this a multi-objective model we allow for the capacity expansion decision maker to evaluate different expansion plans under different criteria, and to obtain a Pareto front of optimal plans. This is relevant, because when having several decision criteria in mind at the same time, a portfolio of optimal investment solutions might be more desirable to have than just one set of investment decisions.
3) To provide a tool for assisting the investment decision making process to determine European Commission (EC) support, analyzing the different investment options.

To our best knowledge, the existing gas market models do not account for points 1 and 2. We propose a multi-objective bi-level optimization model for the representation of the sequential nature of operation and investment decisions in the natural gas market. We define a multi-objective optimization problem [39] in the upper level, considering multiple objective optimization functions for the capacity expansion problem resulting in a set of solutions which represents a good compromise among the objectives, usually known as Edgeworth-Pareto optimum [40,41].

3. Model description

The objective of the model is to assist decision makers in the task of capacity expansion in the natural gas market. For this aim, we propose a multi-objective bi-level optimization model (GASMOPEC), where investments are decided in the upper level under a centralized approach subject to a lower level that represents the gas market operation.

First, the model distinguishes among traders, marketers, gas transportation infrastructure operators (i.e. for natural gas and LNG) and final demand (households, electricity sector and industry). Traders act as gas suppliers to marketers, who are the ones supplying the final demand.

Second, for better representation of the sequential nature of operation and investment decisions and the strategic behavior of market agents in the natural gas sector, the model is formulated as a bi-level optimization problem [42,43], where investment and operation decisions are taken sequentially. In the bi-level model, the network planner chooses capacities that maximize its preferences in the first stage while the second stage represents the Cournot-price-response natural gas market equilibrium.

Third, we assume the EC performs the tasks of a system network planner and acts as a decision maker and as leader investing in new pipeline and regasification capacity. The EC has several criteria that need to be taken into account simultaneously when taking investment decisions. Some criteria that can be highlighted are, total investment costs, utility of demand, price differences between zones, and diversity of suppliers. Depending on the importance assigned to each of these criteria, different optimal investment plans can be obtained.

Fourth, the decisions of the EC (i.e. under the role of network planner) and the market participants, being different entities, are not necessarily going to be the same, and actually might have opposing objectives, such as maximizing social welfare vs maximizing profits of market players. This type of inertia is also captured by a bi-level problem.

Therefore, the problem consists of the objectives of the network planner (i.e. central planner) at the upper level and a lower level that represents the downstream European gas market. In the lower level, the deregulated natural gas market is represented as a generalized Nash-Cournot equilibrium, of successive natural gas trade (i.e. traders representing the upstream and marketers the downstream), in which all agents decide simultaneously. The lower level considers investment decisions as known. The resulting problem is a Mathematical Program with Equilibrium Constraints (MPEC) (see Fig. 1), where the investment decisions are taken first in the upper level, and then operating decisions happen in the lower level.

3.1. Notation

The main notation used is stated below for quick reference.[2]

Indexes	
t	*Traders*
m	*Marketers*
$z,\ z_1$	*Zones*
K_z^{CN}	*Set of consumption nodes*
K_z^{T}	*Set of traders assigned to node z*
K_z^{M}	*Set of marketers assigned to node z*
p	*Periods*
1	
Parameters	
C_{tp}	*Traders' cost per period* (€/bcm)
$P^0_{z_1p}$	*Intercept of demand function per zone and period* (€/bcm)
α_{z_1p}	*Slope of demand per zone and period p* (€/bcm^2)
$\overline{Q}^{tra}_{tzp}$	*Maximum gas volume per trader, zone and period* (bcm)
$\overline{Q}^{pipe}_{zz_1p}$	*Maximum pipeline capacity per zone and period* (bcm)
$\overline{Q}^{liq}_{zp}$	*Maximum liquefaction capacity per zone and period* (bcm)
$\overline{Q}^{reg}_{z_1p}$	*Maximum regasification capacity per zone and period* (bcm)
$TC^{pipe}_{zz_1}$	*Transport cost by pipeline* (€/bcm km)
$TC^{ship}_{zz_1}$	*Transport cost by ship* (€/bcm km)
$COST^{invpipe}_{pzz_1}$	*Investment cost in pipelines* (€/bcm km)
$COST^{invreg}_{pz}$	*Investment cost in new regasification capacity* (€/bcm)
$\overline{CAP}^{invpipe}_{pzz_1}$	*Maximum investment in new pipeline capacity* (bcm)
$\overline{CAP}^{invreg}_{pz}$	*Maximum investment in new regasification capacity* (bcm)
e_{ij}	*Upper and lower reservation levels for each objective function iand case j*
b	*Minimum flow between zones per trader* (bcm)
1	
Variables:	
$q^{tNG}_{tz_1zp}$	*Natural gas sold per trader, zones and period* (bcm)
$q^{tLNG}_{tz_1zp}$	*Liquefied natural gas sold per trader, zones and period* (bcm)
$q^{tpipe}_{tz_1zp}$	*Natural gas transported per trader, between zones and period* (bcm)
$q^{tship}_{tz_1zp}$	*Liquefied natural gas transported per trader, between zones and period* (bcm)
$q^{mak}_{mzz_1p}$	*Marketers' natural gas* (bcm)
$q^{mpipe}_{mzz_1p}$	*Natural gas transported per marketer, between zones and period* (bcm)
$q^{totalpipe}_{zz_1p}$	*Natural gas flow by pipeline per period* (bcm)
$q^{totalship}_{zz_1p}$	*Liquefied natural gas transported per period* (bcm)
bp_{z_1p}	*Dual variable. Gas border price - between traders and marketers* (€/bcm)
p_{z_1p}	*Price in consumption node* (€/bcm)
φ^{tpipe}_{tzp}	*Dual variable of traders' NG flow conservation constraint* (€/bcm)
φ^{tship}_{tzp}	*Dual variable of traders' LNG flow conservation constraint* (€/bcm)
λ^{tra}_{tzp}	*Dual variable. Upper bound on trader's gas available for sale* (€/bcm)
φ^{mak}_{mzp}	*Dual variable of marketers' flow conservation constraint*
$\lambda^{pipe}_{zz_1p}$	*Dual variable. Upper bound on pipeline capacity* (€/bcm)
$\mu^{tNG}_{tzz_1p}$	*Dual variable. Lower bound on NG exports of traders from node z to z₁* ($q^{tNG}_{tzz_1p}$)
$\mu^{tLNG}_{tzz_1p}$	*Dual variable. Lower bound on LNG exports of traders from node z to z₁* ($q^{tLNG}_{tzz_1p}$)
$\mu^{tpipe}_{tzz_1p}$	*Dual variable. Lower bound on NG exports of traders by pipe from z to z₁* ($q^{tpipe}_{tzz_1p}$)
$\mu^{tship}_{tzz_1p}$	*Dual variable. Lower bound on LNG exports of traders by ship from z to z₁* ($q^{tship}_{tzz_1p}$)
$\mu^{mak}_{mzz_1p}$	*Dual variable. Lower bound on marketer's supplies.*($q^{mak}_{mzz_1p}$)
$\mu^{mpipe}_{mzz_1p}$	*Dual variable. Lower bound on marketer's NG flows by pipe.*($q^{mpipe}_{mzz_1p}$)
$\mu^{pipe}_{zz_1p}$	*Dual variable. Lower bound on pipeline's NG flow* $q^{totalship}_{zz_1p}$)
$\mu^{ship}_{zz_1p}$	*Dual variable. Lower bound on LNG flows by ship* ($q^{totalship}_{zz_1p}$)
$cost^{ship}_{zz_1}$	*Dual variable. Total cost LNG transport by ship* (€/bcm)
$i^{pipe}_{pzz_1}$	*Investment in new pipeline capacity* (bcm)
i^{reg}_{pz}	*Investment in new regasification capacity* (bcm)
$cost_{invpipe}$	*Total cost due to investment in new pipeline capacity* (€)
$cost_{invreg}$	*Total cost due to investment in new regasification capacity* (€)
$U(D)$	*Utility of the demand*(€)
Δp_{zz_1p}	*Price difference between zone z and zone* z_1 (€)
$\delta^{tNG}_{zz_1p}$	*Binary variable.* $\delta^{tNG}_{zz_1p} = 1$ *if suppliers tsupplies NG from* zz_1 *in p*
$\delta^{tLNG}_{zz_1p}$	*Binary variable.* $\delta^{tLNG}_{zz_1p} = 1$ *if suppliers t supplies LNG from* zz_1 *in p*

(continued on next column)

(continued)

[2] Bcm stands for billion cubic meters.

3.2. Mathematical problem

3.2.1. Upper level: system operator investment

The capacity expansion problem is represented as a multi-objective considering four different criteria: investment costs, price difference between zones, the utility of the demand and, the number of suppliers. The obtained Pareto frontier supplies a set of solutions, allowing the decision maker to select the best choice according to their preferences.

First, investment costs for new pipeline $cost_{invpipe}$ and regasification $cost_{invreg}$ are minimized. Additionally, we modeled a maximum capacity expansion constraint, for pipelines $\overline{CAP}^{invpipe}_{pzz_1}$ and for regasification terminals $\overline{CAP}^{invreg}_{pz}$ respectively,

$$cost_{invpipe} = \sum_{p,z,z_1}\left(COST^{invpipe}_{pzz_1} \cdot i^{pipe}_{pzz_1}\right) \tag{1}$$

$$i^{pipe}_{pzz_1} \leq \overline{CAP}^{invpipe}_{pzz_1} \forall p, z, z_1 \tag{2}$$

$$cost_{invreg} = \sum_{p,z}\left(COST^{invreg}_{pz} \cdot i^{reg}_{pz}\right) \tag{3}$$

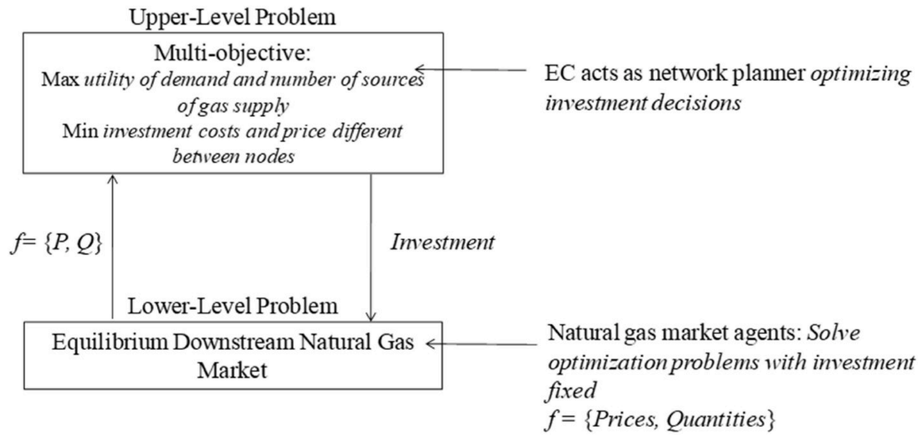

Fig. 1. GASMOPEC model structure MPEC.

$$i^{reg}_{pz} \le \overline{CAP}^{invreg}_{pz} \forall p, z \tag{4}$$

The first objective function (f_1) is therefore:

$$Minimize\ (f_1) = Min\ \{cost_{invpipe} + cost_{invreg}\} \tag{5}$$

Second, we represent the market integration by minimizing the price difference Δp_{zz_1p} between consumption nodes in the objective function, defining Δp_{zz_1p} as a positive variable, and being $p_{z_1p}$the price in the different consumption nodes z, z_1.

$$\Delta p_{zz_1p} \ge p_{zp} - p_{z_1p} \forall\ z, z_1, p\ /\ \{z, z_1 \varepsilon K^{CN}_z\} \tag{6}$$

$$\Delta p_{zz_1p} \ge p_{z_1p} - p_{zp} \forall\ z, z_1, p\ /\ \{z, z_1 \varepsilon K^{CN}_z\} \tag{7}$$

The second objective function (f_2)is:

$$Minimize(f_2) = Min \sum_{zz_1p/\{z,z_1\varepsilon K^{CN}_z\}} (\Delta p_{zz_1p}) \tag{8}$$

Third, the utility of the demand is maximized, in order to fulfill the competition criteria, achieving lower gas supply costs and marginal prices. The total demand in consumption node z_1 is Q_{z_1p}, which includes power generation, industry and households. We assume the inverse demand function p_{z_1p} to be linear of the following type (9).

$$p_{z_1p} = P^0_{z_1p} - \alpha_{z_1p}\cdot Q_{z_1p} = P^0_{z_1p} - \alpha_{z_1p}\cdot \sum_{m,z}\left(q^{mak}_{mzz_1p}\right) \quad \forall\ z_1, p \tag{9}$$

Where $P^0_{z_1p}$ is the intercept of the demand at node z_1 in period p and α_{z_1p} the slope of the demand curve. Therefore, the third objective function (f_3) is maximizing the utility of the demand $U(D)$.

$$Maximize(f_3) = Max\ \{U(D)\} = Max\left\{P^0_{z_1p}\cdot Q_{z_1p} - \frac{\alpha_{z_1p}}{2}\cdot Q^2_{z_1p}\right\} \tag{10}$$

Fourth and last, security of supply is considered by maximizing the number of natural gas supply sources that a country has access to, improving both security of supply and competition. We maximize the number of suppliers that supplies a zone $z_1$using the binary variable $\delta^{tNG}_{zz_1p}$ for natural gas supplies and $\delta^{tLNG}_{zz_1p}$ for liquefied natural gas supplies, as follows. It is assumed that there is only one trader per supplying (producing) country. For natural gas supplies, conditions described in (11) are modeled by constraints (12) and (13). Similarly, conditions described in (14) for liquefied natural gas supplies are modeled by constraints (15) and (16)

$$\delta^{tNG}_{zz_1p} = 1 \leftrightarrow \sum_{t\in z} q^{tNG}_{tzz_1p} \ge b;\ \delta^{tNG}_{zz_1p} = 0 \leftrightarrow \sum_{t\in z} q^{tNG}_{tzz_1p} \le b \tag{11}$$

$$\sum_{t\in z} q^{tNG}_{tzz_1p} - b + \varepsilon \le \delta^{tNG}_{zz_1p}\cdot\left(\left(\overline{Q}^{pipe}_{zz_1p} + \overline{CAP}^{invpipe}_{pzz_1}\right)\right) \forall\ z, z_1, p \tag{12}$$

$$\sum_{t\in z} q^{tNG}_{tzz_1p} - b \ge \cdot\left(1 - \delta^{tNG}_{zz_1p}\right)\cdot(-b) \ \forall\ z, z_1, p \tag{13}$$

$$\delta^{tLNG}_{zz_1p} = 1 \leftrightarrow \sum_{t\in z} q^{tLNG}_{tzz_1p} \ge b;\ \delta^{tLNG}_{zz_1p} = 0 \leftrightarrow \sum_{t\in z} q^{tLNG}_{tzz_1p} \le b \tag{14}$$

$$\sum_{t\in z} q^{tLNG}_{tzz_1p} - b + \varepsilon \le \delta^{tNG}_{zz_1p}\cdot\left(\left(\overline{Q}^{reg}_{z_1p} + \overline{CAP}^{invreg}_{z_1P}\right)\right) \forall\ z, z_1, p \tag{15}$$

$$\sum_{t\in z} q^{tLNG}_{tzz_1p} - b \ge \cdot\left(1 - \delta^{tLNG}_{zz_1p}\right)\cdot(-b) \ \forall\ z, z_1, p \tag{16}$$

Lastly, the fourth objective function (f_4) is:

$$Maximize\ (f_4) = Max \sum_{zz_1p/\{z\varepsilon K^T_z\}\cap\{z\neq z_1\}\cap\{z_1\varepsilon K^M_{z_1}\}} \left(\delta^{tNG}_{zz_1p} + \delta^{tLNG}_{zz_1p}\right) \tag{17}$$

3.2.2. Lower level: downstream natural gas market

Traders act as an interface between the upstream and the downstream gas market. Traders maximize profits of selling gas (i.e. natural gas $q^{tNG}_{tzz_1p}$ and LNG $q^{tLNG}_{tzz_1p}$) to marketers at a price bp_{z_1p} minus the unitary cost of gas C_{tp} and the transport cost for delivering that gas at marketer node by pipe $cost^{pipe}_{zz_1}$ or ship $cost^{ship}_{zz_1}$subject to a volume constraint. We assumed traders charge a fixed cost for their gas. From now on, the dual variables of each constraint are displayed in parenthesis after the colon.

$$\begin{aligned}\underset{q^{tNG}_{tzz_1p},\ q^{tLNG}_{tzz_1p},\ q^{tpipe}_{tzz_1p},\ q^{tship}_{tzz_1p}}{Max} \Pi^{trader}_{tzz_1p} &= bp_{z_1p}\cdot\left(q^{tNG}_{tzz_1p} + q^{tLNG}_{tzz_1p}\right) - C_{tp}\cdot\left(q^{tNG}_{tzz_1p} + q^{tLNG}_{tzz_1p}\right) \\ &- \sum_{(z,z_1)\varepsilon K^{trader}_{tzz_1p}}\left(cost^{pipe}_{zz_1}\cdot q^{tpipe}_{tzz_1p}\right) - \sum_{(z,z_1)\varepsilon K^{trader}_{tzz_1p}}\left(cost^{ship}_{zz_1}\cdot q^{tship}_{tzz_1p}\right) \forall\ t, z, z_1, p\end{aligned} \tag{18}$$

$$s.t.\quad q^{tNG}_{tzz_1p},\ q^{tLNG}_{tzz_1p}, q^{tpipe}_{tzz_1p}, q^{tship}_{tzz_1p} \ge 0\ :\ \left(\mu^{tNG}_{tzz_1p},\ \mu^{tLNG}_{tzz_1p}, \mu^{tpipe}_{tzz_1p}, \mu^{tship}_{tzz_1p}\right) \quad \forall\ t, z, z_1, p \tag{19}$$

The natural gas flow conservation constraint through pipelines for each node z and trader t ensures that the natural gas sold by the traders ($q^{tNG}_{tzz_1p}$) equals natural gas physical flows ($q^{tpipe}_{tzz_1p}$) in all periods p.

$$\left[\sum_{z_1\neq z} q^{tNG}_{tzz_1p} - \sum_{z_1\neq z} q^{tpipe}_{tzz_1p}\right] + \left[\sum_{z_1\neq z} q^{tpipe}_{tz_1zp} - \sum_{z_1\neq z} q^{tNG}_{tz_1zp}\right] = 0\ :\ \left(\varphi^{tpipe}_{tzp}\right) \quad \forall\ t, z, p \tag{20}$$

The same flow conservation constraint applies to the shipped LNG for each node and trader, ensuring that the natural gas sold by the traders

($q^{tLNG}_{tzz_1p}$) equals natural gas physical flows ($q^{tship}_{tzz_1p}$) .

$$\left[\sum_{z_1\neq z} q^{tLNG}_{tzz_1p} - \sum_{z_1\neq z} q^{tship}_{tzz_1p}\right] + \left[\sum_{z_1\neq z} q^{tship}_{tz_1zp} - \sum_{z_1\neq z} q^{tLNG}_{tz_1zp}\right] = 0 \;:\; \left(\varphi^{tship}_{tzp}\right) \quad \forall\, t, z, p \tag{21}$$

The total volume of gas a trader can sell is constrained by $\overline{Q}^{tra}_{tzp}$ that represents the maximum gas available for sale per trader.

$$\sum_{z_1} q^{tNG}_{tzz_1p} + \sum_{z_1} q^{tLNG}_{tzz_1p} \le \overline{Q}^{tra}_{tzp} \;:\; \left(\lambda^{tra}_{tzp}\right) \quad \forall\, t, z, p \tag{22}$$

Finally, the market clearing condition between traders and marketers is (23), where $q^{mak}_{mzz_1p}$is marketers' flows of gas per zone and period. The dual variable of the market clearing equation is the agreed price between traders and marketers.

$$\sum_{t,z} q^{tNG}_{tzz_1p} + \sum_{t,z} q^{tLNG}_{tzz_1p} = \sum_{m,z} q^{mak}_{mzz_1p} \;:\; (bp_{zp}) \quad \forall\, z_1, p \tag{23}$$

Marketers maximize profits buying gas to traders at bp_{zp}, while supplying their gas demand at price p_{z_1p}. The cost paid by the marketer for transporting gas by pipe from node z to z_1 is $cost^{pipe}_{zz_1}$.

$$\begin{aligned} \underset{q^{mak}_{mzz_1p},\, q^{mpipe}_{mzz_1p}}{Max} \Pi^{marketer}_{mzz_1p} &= p_{z_1p}\cdot\left(q^{mak}_{mzz_1p}\right) - bp_{zp}\cdot\left(q^{mak}_{mzz_1p}\right) \\ &- \sum_{(z,z_1)\epsilon K^{marketer}_{mzz_1}} \left(cost^{pipe}_{zz_1}\cdot q^{mpipe}_{mzz_1p}\right) \quad \forall\, m, z, z_1, p \end{aligned} \tag{24}$$

$$s.t. \quad q^{mak}_{mzz_1p},\; q^{mpipe}_{mzz_1p} \ge 0 \;:\; \left(\mu^{mak}_{mzz_1p},\; \mu^{mpipe}_{mzz_1p}\right) \quad \forall\, m, z, z_1, p \tag{25}$$

Finally, the natural gas flow conservation constraint (26) through pipelines for each node z and marketer ensures that the natural gas sold by the marketers $q^{mak}_{mzz_1p}$equals natural gas physical flows $q^{mpipe}_{mzz_1p}$ in all periods.

$$\left[\sum_{z_1\neq z} q^{mak}_{mzz_1p} - \sum_{z_1\neq z} q^{mpipe}_{mzz_1p}\right] + \left[\sum_{z_1\neq z} q^{mpipe}_{mz_1zp} - \sum_{z_1\neq z} q^{mak}_{mz_1zp}\right] = 0 \;:\; \left(\varphi^{mak}_{mzp}\right) \quad \forall\, m, z, p \tag{26}$$

We differentiate between the **System Operator (SO)** who is in charge of the pipelines network operation and the **LNG operator** who is responsible of the LNG liquefaction, shipment and regasification. The available capacity is allocated according to the marginal willingness to pay for the transport by each player (i.e. traders and marketers). Third Party Access (TPA) to the gas network is ensured for all traders and marketers and point-to-point pricing of transport is applied.

The maximization problem of the SO is stated in (27). The price charge by the SO for the use of the network is the dual variable of the market clearing condition (30) between SO and pipeline users (i.e. traders and marketers), which includes the transport costs $TC^{pipe}_{zz_1}$ plus a congestion fee.

$$Max_{q^{totalpipe}_{zz_1p}} \Pi^{pipe}_{zz_1p} = cost^{pipe}_{zz_1}\cdot\left(q^{totalpipe}_{zz_1p}\right) - TC^{pipe}_{zz_1}\cdot\left(q^{totalpipe}_{zz_1p}\right) \quad \forall\, z, z_1, p \tag{27}$$

$$s.t. \;\; q^{totalpipe}_{zz_1p} \ge 0 \;:\; \left(\mu^{pipe}_{zz_1p}\right) \quad \forall\, z, z_1, p \tag{28}$$

The pipeline technical capacity is represented by $\overline{Q}^{pipe}_{zz_1p}$, and $i^{pipe}_{p_1zz_1}$ is the investment in new pipeline capacity.

$$q^{totalpipe}_{zz_1p} \le \overline{Q}^{pipe}_{zz_1p} + \sum_{p_1/p_1<p} i^{pipe}_{p_1zz_1} \;:\; \left(\lambda^{pipe}_{zz_1p}\right) \quad \forall\, z, z_1, p \tag{29}$$

$$q^{totalpipe}_{zz_1p} = \sum_{m/(z,z_1)\epsilon K^{marketer}_{mzz_1}} \left(q^{mpipe}_{mzz_1p}\right) + \sum_{t/(z,z_1)\epsilon K^{trader}_{tzz_1}} \left(q^{tpipe}_{tzz_1zp}\right) \;:\; \left(cost^{pipe}_{zz_1}\right) \quad \forall\, z, z_1, p \tag{30}$$

The maximization problem of the **LNG operator** is stated in (31). The LNG operator receives for the services $cost^{ship}_{zz_1}$, which includes the operation cost $TC^{ship}_{zz_1}$ plus the congestion fee and is the dual variable of the market clearing equation (35).

$$Max_{q^{totalship}_{zz_1p}} \Pi^{ship}_{zz_1p} = cost^{ship}_{zz_1}\cdot\left(q^{totalship}_{zz_1p}\right) - TC^{ship}_{zz_1}\cdot\left(q^{totalship}_{zz_1p}\right) \quad \forall\, z, z_1, p \tag{31}$$

$$s.t. \;\; q^{totalship}_{zz_1p} \ge 0 \;:\; \left(\mu^{ship}_{zz_1p}\right) \quad \forall\, z, z_1, p \tag{32}$$

Upper bound in liquefaction capacity constraint:

$$\sum_{z_1} q^{totalship}_{zz_1p} \le \overline{Q}^{liq}_{zp} \;:\; \left(\lambda^{liq}_{zp}\right) \quad \forall\, z, p \tag{33}$$

Upper bound in regasification capacity constraint:

$$\sum_{z} q^{totalship}_{zz_1p} \le \overline{Q}^{reg}_{z_1p} + \sum_{p_1/p_1<p} i^{reg}_{p_1z z_1} \;:\; \left(\lambda^{reg}_{z_1p}\right) \quad \forall\, z_1, p \tag{34}$$

Market clearing condition between traders with the LNG route operator:

$$q^{totalship}_{zz_1p} = \sum_{t/(z,z_1)\epsilon K^{trader}_{tzz_1}} \left(q^{tship}_{tzz_1zp}\right) \;:\; \left(cost^{ship}_{zz_1}\right) \quad \forall\, z, z_1, p \tag{35}$$

The market clearing condition between marketers and the demand is stated in (9).

3.2.3. Methodological approach

The lower-level of the resulting MPEC problem is stated by its Karush-Kuhn-Tucker (KKT) optimality condition. Lower level KKT conditions are the following:

KKT conditions for the trader's problem

$$-bp_{z_1p} + C_{tp} + \lambda^{tra}_{zp} + \varphi^{tpipe}_{tzp} - \varphi^{tpipe}_{tz_1p} - \mu^{tNG}_{tzz_1p} \ge 0 \quad \perp q^{tNG}_{tzz_1p} \ge 0 \tag{36}$$

$$-bp_{z_1p} + C_{tp} + \lambda^{tra}_{zp} + \varphi^{tship}_{tzp} - \varphi^{tship}_{tz_1p} - \mu^{tLNG}_{tzz_1p} \ge 0 \quad \perp q^{tLNG}_{tzz_1p} \ge 0 \tag{37}$$

$$cost^{pipe}_{zz_1} - \varphi^{tpipe}_{tzp} + \varphi^{tpipe}_{tz_1p} - \mu^{tpipe}_{tzz_1p} \ge 0 \quad \perp q^{tpipe}_{tzz_1p} \ge 0 \tag{38}$$

$$cost^{ship}_{zz_1} - \varphi^{tship}_{tzp} + \varphi^{tship}_{tz_1p} - \mu^{tship}_{tzz_1p} \ge 0 \quad \perp q^{tship}_{tzz_1p} \ge 0 \tag{39}$$

$$\overline{Q}^{tra}_{tzp} - \left(\sum_{z_1} q^{tNG}_{tzz_1p} + \sum_{z_1} q^{tLNG}_{tzz_1p}\right) \ge 0 \quad \perp \lambda^{tra}_{tzp} \ge 0 \tag{40}$$

$$\left[\sum_{z_1\neq z} q^{tNG}_{tzz_1p} - \sum_{z_1\neq z} q^{tpipe}_{tzz_1p}\right] + \left[\sum_{z_1\neq z} q^{tpipe}_{tz_1zp} - \sum_{z_1\neq z} q^{tNG}_{tz_1zp}\right] = 0 \quad \perp \varphi^{tpipe}_{tzp} \tag{41}$$

$$\left[\sum_{z_1\neq z} q^{tLNG}_{tzz_1p} - \sum_{z_1\neq z} q^{tship}_{tzz_1p}\right] + \left[\sum_{z_1\neq z} q^{tship}_{tz_1zp} - \sum_{z_1\neq z} q^{tLNG}_{tz_1zp}\right] = 0 \quad \perp \varphi^{tship}_{tzp} \tag{42}$$

Market clearing condition (23).

KKT conditions for the marketer's problem

$$-p_{z_1p} + bp_{z_1p} + \varphi^{mak}_{mzp} - \varphi^{mak}_{mz_1p} - \mu^{mak}_{mzz_1p} \ge 0 \quad \perp q^{mak}_{mzz_1p} \ge 0 \tag{43}$$

$$cost^{pipe}_{zz_1} - \varphi^{mak}_{mzp} + \varphi^{mak}_{mz_1p} - \mu^{mpipe}_{mzz_1p} \ge 0 \quad \perp q^{mpipe}_{mzz_1p} \ge 0 \tag{44}$$

$$\left[\sum_{z_1\neq z} q^{mak}_{mzz_1p} - \sum_{z_1\neq z} q^{mpipe}_{mzz_1p}\right] + \left[\sum_{z_1\neq z} q^{mpipe}_{mz_1zp} - \sum_{z_1\neq z} q^{mak}_{mz_1zp}\right] = 0 \quad \perp \varphi^{mak}_{mzp} \tag{45}$$

Market clearing condition (9).

KKT conditions for the network operator's problem

$$-cost^{pipe}_{zz_1} + TC^{pipe}_{zz_1} + \lambda^{pipe}_{zz_1p} - \mu^{pipe}_{zz_1p} \ge 0 \quad \perp q^{totalpipe}_{zz_1p} \ge 0 \tag{46}$$

$$\left(\overline{Q}^{pipe}_{zz_1p} + \sum_{p_1/p_1<p} i^{pipe}_{p_1zz_1}\right) - q^{totalpipe}_{zz_1p} \geq 0 \quad \perp \lambda^{pipe}_{zz_1p} \geq 0 \tag{47}$$

Market clearing condition (30).

KKT conditions for the LNG operator's problem

$$-cost^{ship}_{zz_1} + TC^{ship}_{zz_1} + \lambda^{liq}_{zp} + \lambda^{reg}_{z_1p} - \mu^{ship}_{zz_1p} \geq 0 \quad \perp q^{totalship}_{zz_1p} \geq 0 \tag{48}$$

$$\overline{Q}^{liq}_{zp} - \sum_{z_1} q^{totalship}_{zz_1p} \geq 0 \quad \perp \lambda^{liq}_{zp} \geq 0 \tag{49}$$

$$\left(\overline{Q}^{reg}_{zp} + \sum_{p_1/p_1<p} i^{reg}_{p_1zz_1}\right) - \sum_{z_1} q^{totalship}_{zz_1p} \geq 0 \quad \perp \lambda^{reg}_{z_1p} \geq 0 \tag{50}$$

Market clearing condition (35).

Bi-level models are very hard to solve and usually do not allow to scale up to large-scale problems. Therefore, the arising MPEC problem is reformulated as a mixed-integer quadratic problem (MIQCP) by replacing the nonlinear complementarity equilibrium constraints in the lower level by integer restrictions in the form of disjunctive constraints [43,44] using the "Big-M" method. This implies using binary variables and large enough constants (big-Ms). These large enough constants are upper and lower bounds for the primal and dual variables of the lower level problem respectively. Finding the appropriate values for these constants is normally a challenging task. A general definition of this procedure (i.e. Big-M relaxation method) is provided in Ref. [45]. The MIQCP formulation allows solving the problem reliably and the convexity of the problem ensures the globality of the solution. The linearized conditions can be found below. Each set of equations corresponds to the linearization of a complementarity condition. Equality constraints are not included. $\overline{M}_{dual}$, $\underline{M}_{dual}$: Refer to big M parameters corresponding to each dual variable for upper and lower bounds respectively. $\overline{b}_{dual}$, $\underline{b}_{dual}$: refer to binary variables corresponding to each dual variable for upper and lower bounds respectively.

$$\begin{gathered} q^{tNG}_{tzz_1p} \leq \underline{M}_{\mu^{tNG}_{tzz_1p}} \cdot \underline{b}_{\mu^{tNG}_{tzz_1p}} \\ \mu^{tNG}_{tzz_1p} \leq \underline{M}_{\mu^{tNG}_{tzz_1p}} \cdot \left(1 - \underline{b}_{\mu^{tNG}_{tzz_1p}}\right) - bp_{z_1p} + C_{tp} + \lambda^{tra}_{zp} + \varphi^{tpipe}_{tzp} - \varphi^{tpipe}_{tz_1p} - \mu^{tNG}_{tzz_1p} \leq M_{q^{tNG}_{tzz_1p}} \cdot b_{q^{tNG}_{tzz_1p}} \\ q^{tNG}_{tzz_1p} \leq M_{q^{tNG}_{tzz_1p}} \cdot \left(1 - b_{q^{tNG}_{tzz_1p}}\right) \\ \forall t, z, z_1, p \end{gathered} \tag{51}$$

$$\begin{gathered} q^{tLNG}_{tzz_1p} \leq \underline{M}_{\mu^{tLNG}_{tzz_1p}} \cdot \underline{b}_{\mu^{tLNG}_{tzz_1p}} \\ \mu^{tLNG}_{tzz_1p} \leq \underline{M}_{\mu^{tLNG}_{tzz_1p}} \cdot \left(1 - \underline{b}_{\mu^{tLNG}_{tzz_1p}}\right) - bp_{z_1p} + C_{tp} + \lambda^{tra}_{zp} + \varphi^{tship}_{tzp} - \varphi^{tship}_{tz_1p} - \mu^{tLNG}_{tzz_1p} \leq M_{q^{tLNG}_{tzz_1p}} \cdot b_{q^{tLNG}_{tzz_1p}} \\ q^{tLNG}_{tzz_1p} \leq M_{q^{tLNG}_{tzz_1p}} \cdot \left(1 - b_{q^{tLNG}_{tzz_1p}}\right) \\ \forall t, z, z_1, p \end{gathered} \tag{52}$$

$$\begin{gathered} q^{tpipe}_{tzz_1p} \leq \underline{M}_{\mu^{tpipe}_{tzz_1p}} \cdot \underline{b}_{\mu^{tpipe}_{tzz_1p}} \\ \mu^{tpipe}_{tzz_1p} \leq \underline{M}_{\mu^{tpipe}_{tzz_1p}} \cdot \left(1 - \underline{b}_{\mu^{tpipe}_{tzz_1p}}\right) \\ cost^{pipe}_{zz_1} - \varphi^{tpipe}_{tzp} + \varphi^{tpipe}_{tz_1p} - \mu^{tpipe}_{tzz_1p} \leq M_{q^{tpipe}_{tzz_1p}} \cdot b_{q^{tpipe}_{tzz_1p}} \\ q^{tpipe}_{tzz_1p} \leq M_{q^{tpipe}_{tzz_1p}} \cdot \left(1 - b_{q^{tpipe}_{tzz_1p}}\right) \\ \forall t, z, z_1, p \end{gathered} \tag{53}$$

$$\begin{gathered} q^{tship}_{tzz_1p} \leq \underline{M}_{\mu^{tship}_{tzz_1p}} \cdot \underline{b}_{\mu^{tship}_{tzz_1p}} \\ \mu^{tship}_{tzz_1p} \leq \underline{M}_{\mu^{tship}_{tzz_1p}} \cdot \left(1 - \underline{B}_{\mu^{tship}_{tzz_1p}}\right) \\ cost^{ship}_{zz_1} - \varphi^{tship}_{tzp} + \varphi^{tship}_{tz_1p} - \mu^{tship}_{tzz_1p} \leq M_{q^{tship}_{tzz_1p}} \cdot b_{q^{tship}_{tzz_1p}} \\ q^{tship}_{tzz_1p} \leq M_{q^{tship}_{tzz_1p}} \cdot \left(1 - b_{q^{tship}_{tzz_1p}}\right) \\ \forall t, z, z_1, p \end{gathered} \tag{54}$$

$$\begin{gathered} \overline{Q}^{tra}_{tzp} - \left(\sum_{z_1} q^{tNG}_{tzz_1p} + \sum_{z_1} q^{tLNG}_{tzz_1p}\right) \leq \overline{M}_{\lambda^{tra}_{tzp}} \cdot \overline{b}_{\lambda^{tra}_{tzp}} \\ \lambda^{tra}_{tzp} \leq \overline{M}_{\lambda^{tra}_{tzp}} \cdot \left(1 - \overline{b}_{\lambda^{tra}_{tzp}}\right) \\ \forall t, z, p \end{gathered} \tag{55}$$

$$\begin{gathered} q^{mak}_{mzz_1p} \leq \underline{M}_{\mu^{mak}_{mzz_1p}} \cdot \underline{b}_{\mu^{mak}_{mzz_1p}} \\ \mu^{mak}_{mzz_1p} \leq \underline{M}_{\mu^{mak}_{mzz_1p}} \cdot \left(1 - \underline{b}_{\mu^{mak}_{mzz_1p}}\right) - p_{z_1p} + bp_{z_1p} + \varphi^{mak}_{mzp} - \varphi^{mak}_{mz_1p} - \mu^{mak}_{mzz_1p} \leq M_{q^{mak}_{mzz_1p}} \cdot b_{q^{mak}_{mzz_1p}} \\ q^{mak}_{mzz_1p} \leq M_{q^{mak}_{mzz_1p}} \cdot \left(1 - b_{q^{mak}_{mzz_1p}}\right) \\ \forall m, z, z_1, p \end{gathered} \tag{56}$$

$$\begin{gathered} q^{mpipe}_{mzz_1p} \leq \underline{M}_{\mu^{mpipe}_{mzz_1p}} \cdot \underline{b}_{\mu^{mpipe}_{mzz_1p}} \\ \mu^{mpipe}_{mzz_1p} \leq \underline{M}_{\mu^{mpipe}_{mzz_1p}} \cdot \left(1 - \underline{b}_{\mu^{mpipe}_{mzz_1p}}\right) \\ cost^{pipe}_{zz_1} - \varphi^{mak}_{mzp} + \varphi^{mak}_{mz_1p} - \mu^{mpipe}_{mzz_1p} \leq M_{q^{mpipe}_{mzz_1p}} \cdot b_{q^{mpipe}_{mzz_1p}} \\ q^{mpipe}_{mzz_1p} \leq M_{q^{mpipe}_{mzz_1p}} \cdot \left(1 - b_{q^{mpipe}_{mzz_1p}}\right) \\ \forall m, z, z_1, p \end{gathered} \tag{57}$$

$$\begin{gathered} q^{totalpipe}_{zz_1p} \leq \underline{M}_{\mu^{pipe}_{zz_1p}} \cdot \underline{b}_{\mu^{pipe}_{zz_1p}} \\ \mu^{pipe}_{zz_1p} \leq \underline{M}_{\mu^{pipe}_{zz_1p}} \cdot \left(1 - \underline{b}_{\mu^{pipe}_{zz_1p}}\right) - cost^{pipe}_{zz_1} + TC^{pipe}_{zz_1} + \lambda^{pipe}_{zz_1p} - \mu^{pipe}_{zz_1p} \leq M_{q^{totalpipe}_{zz_1p}} \cdot b_{q^{totalpipe}_{zz_1p}} \\ q^{totalpipe}_{zz_1p} \leq M_{q^{totalpipe}_{zz_1p}} \cdot \left(1 - b_{q^{totalpipe}_{zz_1p}}\right) \\ \forall m, z, z_1, p \end{gathered} \tag{58}$$

$$\begin{gathered} \left(\overline{Q}^{pipe}_{zz_1p} + \sum_{p_1/p_1<p} i^{pipe}_{p_1zz_1}\right) - q^{totalpipe}_{zz_1p} \leq \overline{M}_{\lambda^{pipe}_{zz_1p}} \cdot \overline{b}_{\lambda^{pipe}_{zz_1p}} \\ \lambda^{pipe}_{zz_1p} \leq \overline{M}_{\lambda^{pipe}_{zz_1p}} \cdot \left(1 - \overline{b}_{\lambda^{pipe}_{zz_1p}}\right) \\ \forall z, z_1, p \end{gathered} \tag{59}$$

$$\begin{gathered} q^{tship}_{tzz_1zp} \leq \underline{M}_{\mu^{ship}_{zz_1p}} \cdot \underline{b}_{\mu^{ship}_{zz_1p}} \\ \mu^{ship}_{zz_1p} \leq \underline{M}_{\mu^{pipe}_{zz_1p}} \cdot \left(1 - \underline{b}_{\mu^{pipe}_{zz_1p}}\right) - cost^{ship}_{zz_1} + TC^{ship}_{zz_1} + \lambda^{liq}_{zp} + \lambda^{reg}_{z_1p} - \mu^{ship}_{zz_1p} \leq M_{q^{tship}_{tzz_1zp}} \cdot b_{q^{tship}_{tzz_1zp}} \\ q^{tship}_{tzz_1zp} \leq M_{q^{tship}_{tzz_1zp}} \cdot \left(1 - b_{q^{tship}_{tzz_1zp}}\right) \\ \forall t, z, z_1, p \end{gathered} \tag{60}$$

$$\begin{aligned}&\overline{Q}^{liq}_{zp} - \sum_{z_1} q^{totalship}_{zz_1p} \leq \overline{M}_{\lambda^{liq}_{zp}} \cdot \overline{b}_{\lambda^{liq}_{zp}}\\ &\lambda^{liq}_{zp} \leq \overline{M}_{\lambda^{liq}_{zp}} \cdot \left(1 - \overline{b}_{\lambda^{liq}_{zp}}\right)\\ &\forall\, z, p\end{aligned} \tag{61}$$

$$\begin{aligned}&\left(\overline{Q}^{reg}_{zp} + \sum_{p_1/p_1<p} i^{reg}_{p_1zz_1}\right) - \sum_{z_1} q^{totalship}_{zz_1p} \leq \overline{M}_{\lambda^{reg}_{z_1p}} \cdot \overline{b}_{\lambda^{reg}_{z_1p}}\\ &\lambda^{reg}_{z_1p} \leq \overline{M}_{\lambda^{reg}_{z_1p}} \cdot \left(1 - \overline{b}_{\lambda^{reg}_{z_1p}}\right)\\ &\forall\, z, p\end{aligned} \tag{62}$$

For solving the multi-objective problem stated in the upper level and computing the non-dominated solutions, we use the e-constraint scalarizing technique [46], which enables us to obtain all non-dominated solutions, (i.e., solutions lying on edges or faces and vertices) of the feasible region of the original multi-objective problem even if the decision space is discrete (MIQCP problem). This scalarization technique selects one of the i objective functions (f_i) to be optimized considering the other $(i-1)$ objectives as constraints by specifying the upper and the lower levels that the decision maker is willing to accept.

In the problem, the utility of the demand is maximized considering the other three objectives (i.e. minimizing investment cost and price difference between zones, and maximizing the number of natural gas supply sources) as constraints by specifying their reservation levels. The utility of the demand is the criteria with less variation range. The reservation levels selected for the rest of criteria are defined as follows: first, for the investment criteria, we assume it varies from zero (i.e. no investment) to the maximum investment capacity defined for each type of infrastructure (i.e. pipeline or regasification terminal); second, for assigning price difference between zones reservation levels, the problem is run considering this criterion as the unique objective, without allowing any investment. The obtained optimal point will be the maximum price difference allowed between zones. The minimum price difference allowed is calculated also by considering this criterion as the unique objective but allowing for maximum investment capacity; third, the range for the number of suppliers varies from the minimum number of gas suppliers (i.e. NG and LNG), which is determined by running the problem considering this criterion as the unique objective, without allowing any investment, and the maximum which is calculated by multiplying the number of suppliers by the number of zones assuming all suppliers can supply all zones.

Additionally, in order to avoid obtaining weakly efficient solutions the $(i-1)$ objective functions that are set as constraints are included in the objective function multiplied by $\rho_i > 0$, small positive scalars.

$$Max\, f_3(x) - \rho_1 \cdot f_1(x) - \rho_2 \cdot f_2(x) + \rho_4 \cdot f_4(x) \tag{63}$$

$$s.t.\ x \in X; f_1(x) \leq e_1;\ f_2(x) \leq e_2;\ f_4(x) \geq e_4 \tag{64}$$

The problem is solved repeatedly assigning different parameters for each objective function $i$and case j, (e_{ij}) to generate non-dominated solutions for the optimal investment plan, and can be interpreted as a measure of importance given by the decision maker (network expansion planner)

4. Case study

The proposed model is used for the assessment of the optimal infrastructure investment in the North-South Gas Interconnections in Western Europe under a market price perspective.

4.1. Description

We consider the following nodes of the NSI West Gas corridor: Benelux (The Netherlands, Belgium and Luxemburg) (BE), France (FR), Germany (GE), Italy (IT), Spain (ES) and the United Kingdom (UK). The most representative exporters (i.e. traders) to the EU are included: Russia (RU), Algeria (DZ), the European producers (Norway (NO) and the Netherlands (NE)) and GNL of Middle East (represented by Qatar (QT)).

The case study data ranges from years 2015–2035, in ten-year steps. We use production capacity and consumption demand data from Ref. [47] for the base year. Production and consumption projections for the ten years forward are based on [48] New Policies Scenario (NPS). Prices are taken from Ref. [49] and we apply the growth rates published by the OECD in 2017. Data on transport capacity and regasification terminals are based on the ENTSO-G information 2017 and [50]. We aggregate bilateral transport capacities for pairs of zones. Production costs are taken from Refs. [51] and own estimations. As we focus on the long-term, we do not distinguish among seasons and hence the possible arbitrage game of the underground storage is not represented. Transportation costs within Europe are represented as costs per unit of gas and km of average distance between countries as based on [51]. Investment costs have been taken from Refs. [21], assuming them to be a multiple of the short-term transportation costs, both depending on the pipeline length.

The equilibrium problem has been recast as a mixed-integer quadratic problem, implemented in the GAMS language and solved by using Gurobi version 7.5.2.

5. Results

We run 50 cases($j = 50$), varying the upper and lower objective functions (i) reservation levels (e_{ij}) of the constraints for computing the non-dominated solutions, which are the closest feasible compromise solutions, considering the contour conditions.

The allowed investment is increased from case 1 to 50. For each allowed investment capacity, different reservation levels (i.e. inside the range previously defined) for the number of gas suppliers and price differences between zones are run. While we decrease the number of gas suppliers we increase the permitted price difference.

When interpreting the presented results, the following important points need to be borne in mind: First, it should be noted that Western Europe is well interconnected and the model does not invest endogenously in any pipeline or regasification capacity considering all the criteria with the same importance. Moreover, no investment is compensated in terms of utility of the demand. This means that the investment cost exceeds the positive impact in the utility of the demand. Second, some zones have been clustered (i.e. Spain and Portugal or Ireland and UK) and no investment within countries is considered. Third, there are other reasons for investment such as system security and its robustness and short-term market operation, which are not considered in the model.

In the first ten cases no investment is allowed. From case 1 to 10 the maximum permitted price difference is increased while the requested minimum number of suppliers is diminished. The utility of the demand increases as the average price difference between nodes increases and the number of suppliers decreases. Reducing price difference between nodes, in this case is at the expenses of reducing the utility of the demand, by reducing prices at consumption node (see Fig. 2). The number of NG suppliers is constant among these cases. Forcing a maximum of LNG suppliers implies that the marketers have access to more expensive sources of gas to fulfill this constraint, and as a result we obtained that marketers import marginal volumes of Norwegian LNG gas.

New investments can affect the utility of the demand by driving changes in the gas supply, connecting to new sources of gas, by bringing more gas reducing bottlenecks or favoring price convergence. When we allow some investment (cases from 11 to 21) (i.e. defining a maximum in the investment capacity) the model invests in regasification capacity in the United Kingdom (UK) and France (FR) up to the maximum allowed (6 Bcm/y) (See Fig. 3). Both of them already have regasification capacity (i.e. UK: 48.1 Bcm/y and FR: 21.65 Bcm/y (34.25 Bcm/y in 2025

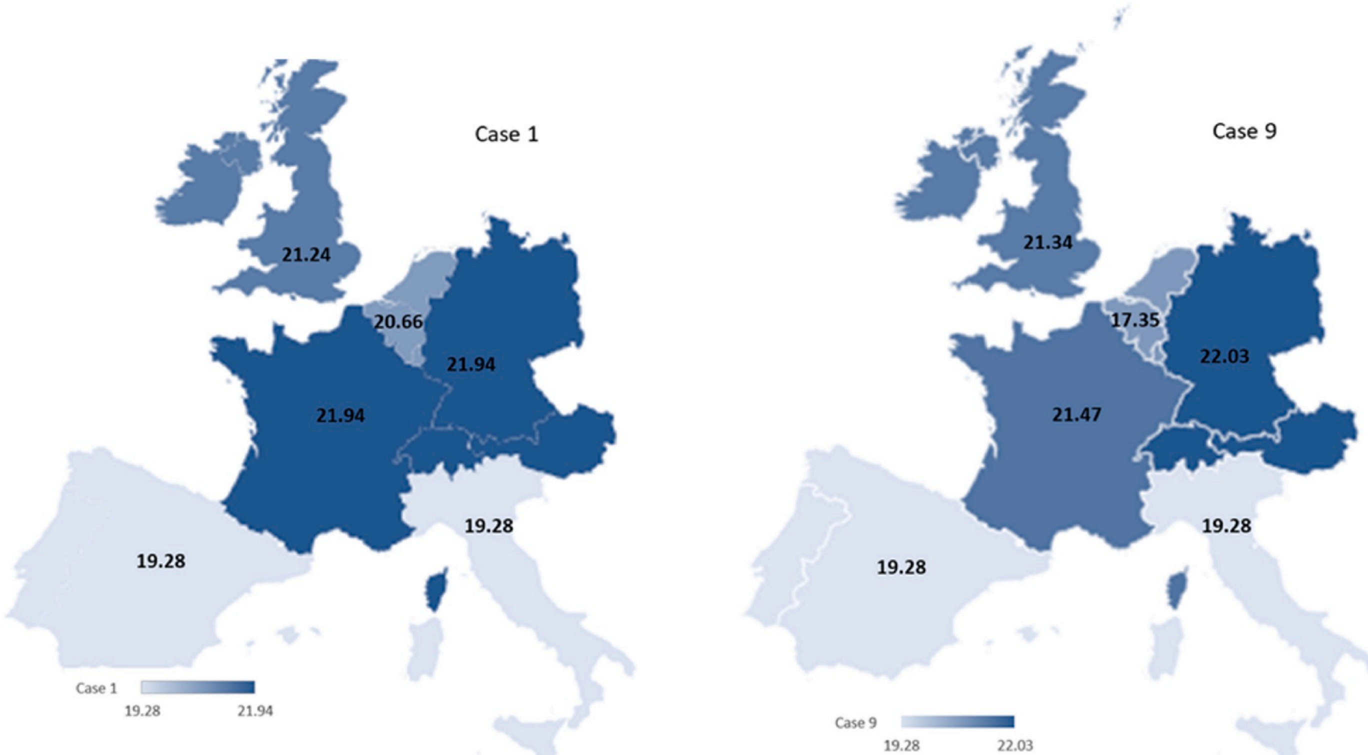

Fig. 2. Cases 1 and 9. No investment is allowed. Prices (EUR/MWh) per consumption mode and investment in pipelines and regasification capacity.

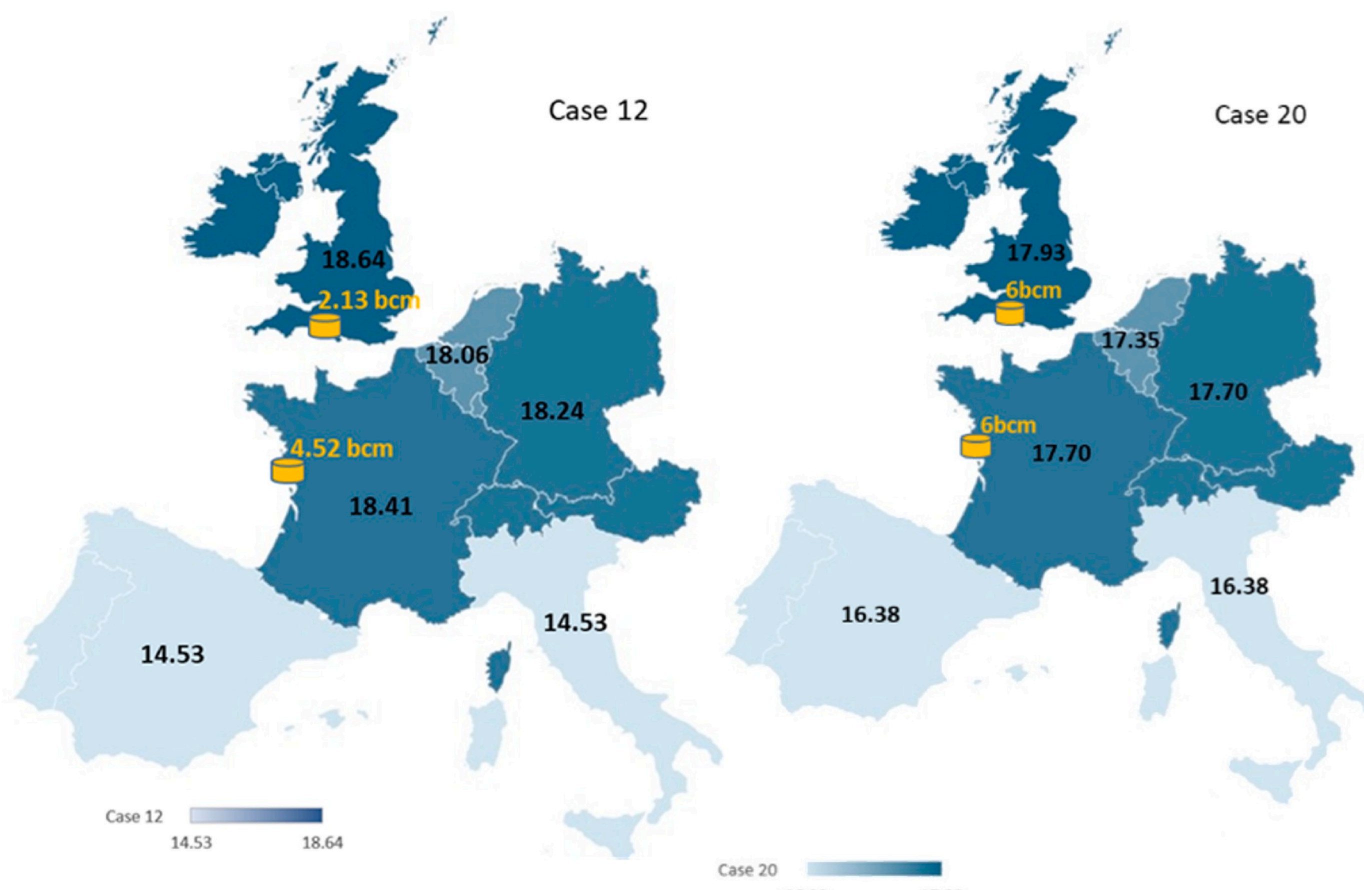

Fig. 3. Cases 12 and 20. Prices (EUR/MWh) per consumption mode and investment in pipelines and regasification capacity.

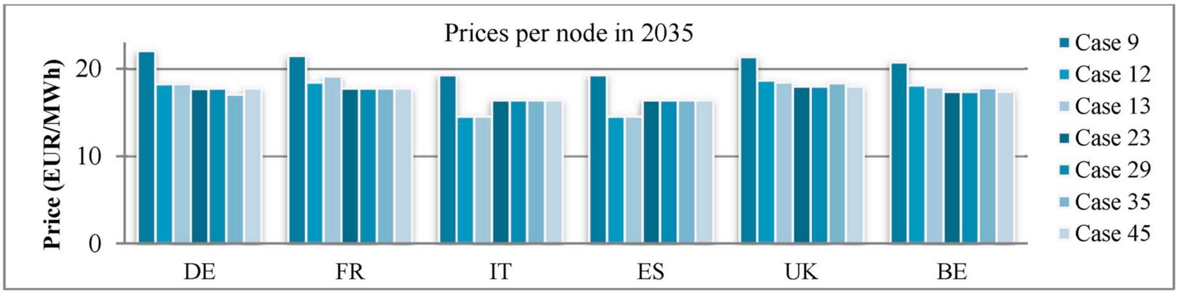

Fig. 4. Prices (EUR/MWh) per country (consumption nodes) in 2035 for some representative cases.

exogenous expansion)), so that both countries have already access to LNG markets. However, the model doesn't invest in pipeline capacity. The investment in regasification capacity has a positive effect by reducing gas prices in the consumption nodes, as shown in Fig. 4 (i.e. cases 9, 12 and 13) and therefore increasing the utility of the demand.

As more investment is allowed (cases from 22 to 26), the model invests in new pipeline capacity between Algeria – Spain (4.95 Bcm/y), Algeria – Italy (7.48 Bcm/y), Italy – Germany (0.22 Bcm/y), Italy – France (8.70 Bcm/y), Norway – Belgium (2.16 Bcm/y)), Russia – Germany (18.64 Bcm/y) and Russia – Italy (7.98 Bcm/y) in addition to the investment in regasification capacity in France and the United Kingdom. These cases present similar weights (i.e. given preference) for the different criteria. The investment in new pipeline capacity reduces price difference between zones but its impact in terms of utility of the demand is almost negligible. Converging prices is a sign of well-integrated markets and cooperation between MSs. Prices in Italy and Spain increased in favor of a price reduction in France and Germany as shown in Case 23. The maximum price differences appear between the Italian and the French market and between the Italian and the British market. In cases from 30 to 32 and from 35 to 36, even if permitted investment is increased, the model invests less globally, reducing the investment among EU countries (i.e. Italy – Germany (0.17 Bcm/y), Norway-Belgium (1.48 Bcm/y)). The price difference is diminished and also the number of LNG suppliers. However, Belgium gas market price increases as it imports less Norwegian gas.

The pipeline from Norway – Belgium is replaced in latter cases by more regasification capacity in Belgium (5.39 Bcm/y) (i.e. such as 33 and cases from 40 to 50) and the average price convergence is improved.

Even if more investment is allowed, from cases 40 to 50, the model doesn't invest in further additional capacity. This means that up to a certain point investment in new capacity will not add any additional benefit in terms of utility of the demand, price convergence or increasing the number of suppliers. This plateau is represented by the following investments: Algeria – Spain (4.95 Bcm/y), Algeria – Italy (7.48 Bcm/y), Italy – Germany (0.17 Bcm/y), Italy – France (8.75 Bcm/y), Russia – Germany (18.64 Bcm/y) and Russia – Italy (7.98 Bcm/y), and the following regasification capacity: Belgium (5.39 Bcm/y), France (6 Bcm/y) and United Kingdom (6 Bcm/y).

In this case study, when marketers are obliged to diversify their gas supply portfolio, their total costs increase, and it is reflected in the market price (i.e. final market prices rise). Additionally, it doesn't help to price convergence between nodes or the creation of the internal market, as these new suppliers are not reached via pipeline by connecting the MSs but via regasification capacity or increasing pipeline capacity with incumbent major gas suppliers (i.e. Algeria and Russia).

In Fig. 5, cases 26, 33 and 40 are compared. The investment in 8.7 bcm of pipeline capacity between Italy and France, reduces French prices in 0.47 €/MWh increasing flows between Italy and France. In the case of the Benelux zone, prices are reduced 0.45 €/MWh by investing 5.39 bcm in regasification capacity in case 33 instead of investing in additional pipeline capacity with Norway, as in case 26.

For more detailed results, please refer to Table 1.

6. Conclusions

In this paper we propose a model whose objective is to represent a realistic decision-making process for analyzing the optimal infrastructure investments in natural gas pipelines and regasification terminals within the EU framework under a market perspective. Thus, in order to represent that expansion and operation decisions are taken sequentially, the different interest of market participants and the multiple criteria that need to be achieved simultaneously (i.e. market integration, security of supply, competition), we propose a multi-objective bi-level optimization model for representing the investment decision process in the European

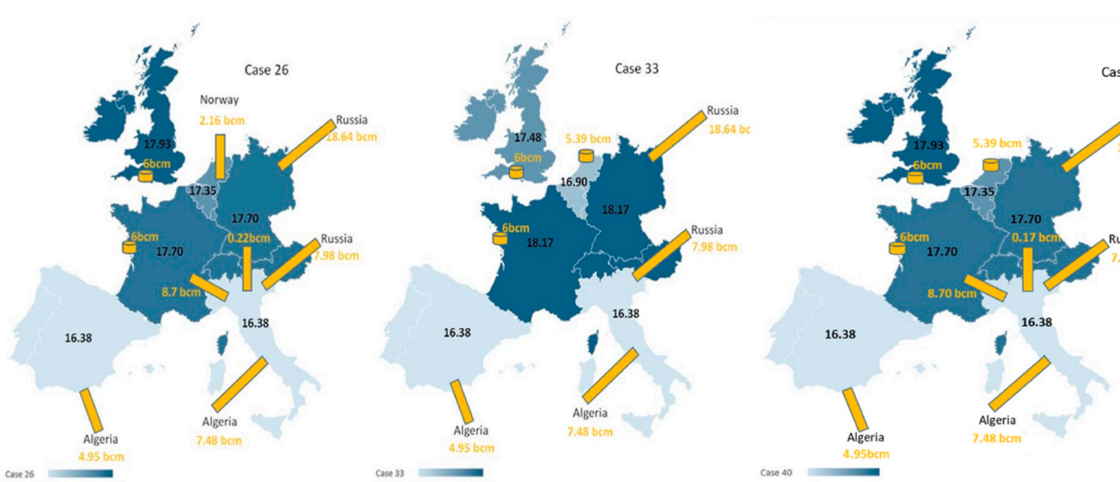

Fig. 5. Cases 26, 33 and 40. Prices (EUR/MWh) per consumption mode and investment in pipelines and regasification capacity.

natural gas market (GASMOPEC). The model consists of the objectives of the network planner at the upper level optimizing a multi-objective function and a lower level that represents the downstream European gas market. The contribution of this paper is three-fold.

First, we introduce the natural sequence of investment and operation decisions into a gas market model covering the existing gap found in the literature regarding bi-level optimization models applied to investment in natural gas markets.

Second, by using a multi-objective model we allow for the capacity expansion decision maker to evaluate different expansion plans under different criteria (i.e. minimizes network investment and price difference between zones, and maximizes utility of demand and number of gas suppliers) obtaining a portfolio of optimal investment solutions (i.e. non-dominated solutions of optimal plans).

Third, we provide a tool for assisting the investment decision making process, analyzing the different investment options.

The proposed model is used for the assessment of the optimal infrastructure investment in Western Europe. From the simulation and the analysis of the different cases in the case study, we draw several conclusions. First, Western Europe is well interconnected and no investment cost exceeds the positive impact yielded by the investment in terms of the utility of the demand. This means that additional incentives for enhancing investment should be considered for those infrastructures which are considered as key or of common interest (i.e. market integration, price convergence, security of supply, competition and sustainability). Second, the model invests in two regasification terminals in France and the United Kingdom, improving the utility of the demand. Third, the pipeline capacity with incumbent major gas suppliers (i.e. Algeria and Russia) increases, falling into disfavor with market integration (i.e. connecting Member States) or diversification of sources of gas supply.

Appendix A

Appendix results

The following table shows the obtained results for the 50 cases, presenting the total investment in pipeline and regasification capacity, the utility of the demand, the average price difference between nodes, and the number of LNG suppliers.

Table 1
Case study results. Total investment in new pipeline and regasification capacity, utility of the demand, average price difference between nodes and number of LNG suppliers.

Case	Pipeline In-Out nodes (Bcm annual)	Reg. Terminal N Node (Bcm annual)	Utility of the demand (Million EUR)	Average price difference (EUR/MWh)	Suppliers*
1	–	–	1.0383	0.97	41
2	–	–	1.0384	1.07	41
3	–	–	1.0387	1.31	39
4, 5, 6, 7	–	–	1.0384	1.07	39
8	–	–	1.0387	1.29	38
9	–	–	1.0388	1.37	38
10	–	–	1.0388	1.39	38
11	–	**FR** (2.13); **UK** (4.52)	1.0798	1.22	38
12	–	**FR** (2.13); **UK** (4.52)	1.0820	1.65	38
13,14	–	**FR** (0.95); **UK** (5.71)	1.0814	1.26	38
			1.0818	1.43	38
15	–	**FR** (3.74); **UK** (2.92)	1.0817	1.49	38
16, 17	–	**FR** (4.02); **UK** (2.63)	1.0818	1.43	38
18	–		1.0814	1.26	38
19	–	**FR** (6.00); **UK** (6.00)	1.0805	0.87	38
20, 21	–		1.0812	1.24	38
22,	**DZ-ES** (4.95); **DZ-IT** (7.48); **IT-DE** (0.22); **IT-FR**	**FR** (6.00); **UK** (6.00)	1.0813	1.23	36
23, 24, 25,	(8.70); **NO-BE** (2.16);				37
26	**RU-DE** (18.64); **RU-IT** (7.98);				
27, 33	**DZ-ES** (4.95); **DZ-IT** (7.48);	**BE** (5.39);**FR** (6.00); **UK**	1.0808	1.04	35
28	**RU-DE** (18.64); **RU-IT** (7.98)	(6.00)	1.0813	1.24	35
29	**DZ-ES** (4.95),**DZ-IT** (7.48); **IT-DE** (0.17);	**BE** (5.39)	1.0811	0.93	35
39	**IT-FR** (8.70); **RU-DE** (18.64);	**BE** (5.39), **FR** (6.00); **UK**	1.0815	1.33	35
40	**RU-IT** (7.98)	(6.00)	1.0820	1.59	35
41, 45			1.0820	1.61	35
42, 48			1.0817	1.39	35
43, 46			1.0809	0.99	35
44			1.0820	1.59	35
47, 50			1.0820	1.59	35
48			1.0817	1.39	35
49			1.0811	1.04	35
30, 31, 32,	**DZ-ES** (4.95); **DZ-IT** (7.48);	**FR** (6.00); **UK** (6.00)	1.0810	0.93	34
35	**IT-DE** (0.17);**IT-FR** (8.70); **NO-BE** (1.48); **RU-DE**				
36	(18.64); **RU-IT** (7.98)		1.0808	1.01	34
37			1.0810	0.98	34
34	**DZ-ES** (4.95); **DZ-IT** (7.48);**IT-DE** (0.18); **RU-DE** (18.64); **RU-IT** (7.98)	**BE** (5.39);**FR** (6.00); **UK** (6.00)	1.0813	1.23	34
38	**DZ-ES** (4.95); **DZ-IT** (7.48); **RU-DE** (18.64); **RU-IT** (7.98); **UK-BE** (3.23)	**BE** (5.39);**FR** (6.00); **UK** (6.00)	1.0811	1.02	35

^**Notes to table:** The number of LNG suppliers is the summation of the number of suppliers in the three periods. The number of NG suppliers is 34 for cases from 1 to 28 and 31 for cases from 29 to 50. Cases which yield the same solutions have been clustered.

Appendix B. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.esr.2020.100492.

References

[1] ENTSOG, Second ENTSOG methodology for cost-benefit analysis of gas infrastructure projects, Draft for ACER and Commission opinions (2017) 1–80, no. INV0256-17.
[2] S.A. Gabriel, A. Kydes, P. Whitman, The national energy modeling system: a large-scale energy- economic equilibrium model, Operations Research," *Oper. Res.* 49 (November 2017) (2001) 14–25.
[3] EIA, The National Energy Modeling System: an Overview 2009, 2009. Washington, DC.
[4] J. Perner, A. Seeliger, Prospects of gas supplies to the European market until 2030 - results from the simulation model EUGAS, Util. Pol. 12 (4) (2004) 291–302.
[5] S. Lochner, D. Bothe, "The development of natural gas supply costs to Europe , the United States and Japan in a globalizing gas market — model-based analysis until 2030, Energy Pol. 37 (2009) 1518–1528.
[6] S. Lochner, C. Dieckhöner, D. Linderberger, Model-based analysis of market integration and congestion in the European gas market, in: 9th Conference on Applied Infrastructure Research, 2010.
[7] S. Lochner, Identification of congestion and valuation of transport infrastructures in the European natural gas market, Energy 36 (5) (2011) 2483–2492.
[8] C. Dieckhöner, Simulating security of supply effects of the nabucco and South stream projects for the European natural gas market, Energy J. 33 (3) (2012) 153–182.
[9] C. Dieckhöner, S. Lochner, D. Lindenberger, European natural gas infrastructure: the impact of market developments on gas flows and physical market integration, Appl. Energy 102 (2013) (2013) 994–1003.
[10] L. Hellemo, K. Midthun, A. Tomasgard, A. Werner, Natural gas infrastructure design with an operational perspective, Energy Procedia 26 (2012) 67–73.
[11] M. Fodstad, R. Egging, K. Midthun, A. Tomasgard, Stochastic Modeling of Natural Gas Infrastructure Development 37 (2016) 1–28.
[12] A. Kiss, A. Selei, T. Borbála Takácsné, A top-down approach to evaluating cross-border natural gas infrastructure projects in Europe, 2016, pp. 1–19.
[13] A. Haurie, Q.G. d'études, et de recherche en analyse des décisions, École des hautes études commerciales (Montréal, "A stochastic dynamic Nash-Cournot model for the European gas market. Montréal: École des hautes études commerciales, Montréal, 1987, 1987.
[14] L. Mathiesen, On Modeling the European Market for Natural Gas, Bergen, 2001.
[15] R. Golombek, E. Gjelsvik, K.E. Rosendahl, Memorandum from University of Oslo, 1994.
[16] R. Golombek, E. Gjelsvik, K.E. Rosendahl, Increased competition on the supply side of the western European natural gas market, Energy J. 19 (3) (1998) 1–18.
[17] M.G. Boots, F.a.M. Rijkers, B.F. Hobbs, GASTALE: an Oligopolistic Model of Production and Trade in the European Gas Market, 2003, pp. 1–36. August.
[18] M.G. Boots, F.a.M. Rijkers, B.F. Hoobs, Trading in the downstream euroean gas market A succesive oligopoly Approach.pdf, Energy J. 25 (3) (2004).
[19] W. Lise, B.F. Hobbs, Future Evolution of the Liberalised European Gas Market: Simulation Results with a Dynamic Model, vol. 33, 2008, pp. 989–1004.
[20] G. Zwart, M. Mulder, "NATGAS: a Model of the European Natural Gas Market," *CPB Memorandum*, CPB Netherlands Bureau for Economic Policy Analysis, 2006.
[21] F. Holz, "Modeling the European Natural Gas Market — Static and Dynamic Perspectives of an Oligopolistic Market, Technische University at Berlin, 2009.
[22] A.A. Bornaee, Dealing with Investment Uncertainties in the European Natural Gas Market A Stochastic Equilibrium Model for the European Natural Gas Market, Faculty of Technology, policy and management, TUDELFT, 2012.
[23] R.G. Egging, S.A. Gabriel, Examining market power in the European natural gas market, Energy Pol. 34 (17) (2006) 2762–2778.
[24] R.G. Egging, F. Holz, S.A. Gabriel, The World Gas Model A Multi-Period Mixed Complementarity Model for the Global Natural Gas Market, 2009.
[25] R.G. Egging, Multi-Period Natural Gas Market Modeling Applications, Stochastic Extensions and Solution Approaches, 2010.
[26] R.G. Egging, "Benders Decomposition for multi-stage stochastic mixed complementarity problems – applied to a global natural gas market model, Eur. J. Oper. Res. 226 (2) (2013) 341–353.
[27] F. Holz, C. Von Hirschhausen, "The infrastructure implications of the energy transformation in Europe until 2050 — lessons from the Emf28 modeling exercise, Clim. Chang. Econ. 4 (supp01) (2013) 1340006.
[28] F. Holz, P.M. Richter, R.G. Egging, The Role of Natural Gas in a Low-Carbon Europe: Infrastructure and Regional Supply Security in the Global Gas Model, 2013.
[29] R.G. Egging, F. Holz, "Risks in global natural gas markets: investment , hedging and trade, Energy Pol. 94 (2016) 468–479.
[30] Y. Smeers, Gas Models and Three Difficult Objectives, 2008.
[31] J. Bracken, J.T. McGill, Mathematical programs with optimization prob- lems in the constraints, Oper. Res. 21 (1973) 37–44.
[32] J. Bracken, J.T. McGill, Equivalence of two mathematical programs with optimization problems in the constraints, Oper. Res. 22 (1974) 1102–1104.
[33] J. Bracken, J.T. McGill, A method for solving mathematical programs with nonlinear programs in the constraints, Oper. Res. (1974) 1097–1101.
[34] C.-L. Su, Equilibrium Problems with Equilibrium Constraints: Stationarities, Algorithms, and Applications, Stanford University, 2005.
[35] D. De Wolf, Y. Smeers, A stochatis version of a stackelberg-nash cournot euqilibrium model, Manag. Sci. 43 (1997).
[36] V.V. Kalashnikov, R.Z. Ríos-Mercado, A natural gas cash-out problem: a bilevel programming framework and a penalty function method, Optim. Eng. 7 (4) (2006) 403–420.
[37] S. Siddiqui, S.A. Gabriel, An SOS1-based approach for solving MPECs with a natural gas market application, Network. Spatial Econ. 13 (2) (2013) 205–227.
[38] G. Li, R. Zhang, T. Jiang, H. Chen, L. Bai, X. Li, Security-constrained bi-level economic dispatch model for integrated natural gas and electricity systems considering wind power and power-to-gas process, Appl. Energy 194 (2017) 696–704.
[39] C.A. Coello Coello, Evolutionary multi-objective optimization: a historical view of the field, IEEE Comput. Intell. Mag. 1 (1) (2006) 28–36.
[40] F.Y. Edgeworth, Mathematical Physics, P. Keagan, London, 1881.
[41] V. Pareto, "Cours D'Economie Politique, Volume I and II, F. Rouge, Lausanne, 1896.
[42] S. Wogrin, E. Centeno, J. Barquín, "Generation capacity expansion analysis: open loop approximation of closed loop equilibria, IEEE Trans. Power Syst. 28 (3) (2013) 3362–3371.
[43] C.A. Coello Coello, Evolutionary multi-objective optimization: a historical view of the field, IEEE Comput. Intell. Mag. 1 (1) (2006) 28–36.
[44] S.A. Gabriel, Y. Shim, A.J. Conejo, S. De Torre, R. Garcia, A Benders decomposition method for discretely- constrained mathematical programs with equilibrium constraints, J. Oper. Res. Soc. (2010) 1404–1419.
[45] S. Pineda, J.M. Morales, Solving linear bilevel problems using big-ms: not all that glitters is gold, IEEE Trans. Power Syst. 34 (3) (2019) 2469–2471, https://doi.org/10.1109/TPWRS.2019.2892607.
[46] C.H. Antunes, M.J. Alves, J. Clímaco, Multiobjective Linear and Integer Programming, 2016.
[47] British Petroleum (BP), BP Statistical Review of World Energy 2017, 2017.
[48] [IEA] - International Energy Agency, World Energy Outlook, 2016, 2016.
[49] European Commission, Quarterly Report on European Gas Markets, Market Obsevatory for Energy, 2015.
[50] International Gas Union (IGU), "World LNG Report – 2017 Edition, 2017.
[51] F. Holz, C. von Hirschhausen, C. Kemfert, A strategic model of European gas supply (GASMOD), Energy Econ. 30 (3) (2008) 766–788.