# Implementation of a Hub to capture individual profit-maximizing behavior in the gas market

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## Abstract

The gas market situation in Europe has changed considerably with the liberalization of the gas industry as the introduction of competition has increased the interaction among shippers. The 3rd EU Gas Directive (2009/73/EC) establishes the constitution of national or supra-national virtual hubs to enlarge the market. This that has led to the emergence of balancing zones and trading hubs in Europe that are introducing flexibility in the markets and reducing transaction costs. The objective of this paper is to represent the strategic behavior of shippers operating in the natural gas market, while representing the market operation in detail and to analyze the impact of introducing a hub in the downstream natural gas market.

## Keywords

Natural gas market, optimization models, market balance, entry-exit access system.

## Notation

### *Sub-indexes*

| | |
|---|---|
| $p$ | *Index of periods* |
| $e$ | *Index of shipper* |
| $q$ | *Index of contract* |
| $r$ | *Index of LNG regasification plant* |
| $i$ | *Index of international LNG market* |
| $x$ | *Index of cross-border pipeline* |
| $z$ | *Index of balancing zone* |
| $s$ | *Index of underground storage* |
| $b$ | *Index of LNG carriers* |
| $t$ | *Index of gas quantity blocks* |

## *Parameters*

| | |
|---|---|
| $D_{p,e}^{TOT}$ | *Total demand in balancing zone z of shipper e in period p [GWh]* |
| $\overline{V}_{p,q,e}^{DIV}$ | *Maximum diverted volume of supply contract q delivered to shipper e during year y [GWh]* |
| $Slp_{p,z,e,t}^{OFR}$ | *Slope of the offer block t in the hub located in the balancing zone z by shipper e in period p [€/GWh]* |
| $Slp_{p,z,e,t}^{BID}$ | *Slope of the bidding block t in the hub located in the balancing zone z by shipper e in period p [€/GWh]* |
| $Int_{p,z,e,t}^{OFR}$ | *Intercept of the offer block t in the hub located in the balancing zone z by shipper e in period p [€]* |
| $Int_{p,z,e,t}^{BID}$ | *Intercept of the bidding block t in the hub located in the balancing zone z by shipper e in period p [€]* |
| $Spr_{p,z,e}^{OFR}$ | *Spread of the offer curve t in the hub located in the balancing zone z by shipper e in period p [€]* |
| $Spr_{p,z,e}^{BID}$ | *Spread of the bidding curve t in the hub located in the balancing zone z by shipper e in period p [€]* |

## *Variables:*

| | |
|---|---|
| $V_{p,q,e,q',e'}^{Supplied}$ | *Volume supplied by company e' from its contract q' to company e through a bilateral contract q in period p [GWh]* |
| $V_{p,q,e}^{Bilateral}$ | *Volume received by company e from a bilateral contract q in period p [GWh]* |
| $V_{p,q,e}^{Total}$ | *Total volume received from contract q in period p due to supply contract q* |
| $V_{p,i,r,q,e}^{MET}$ | *Delivered LNG volume from international market i at regasification terminal r due to supply contract q of shipper e in period p [GWh]* |
| $V_{p,x,z,q,e}^{IMP}$ | *Imported volume by cross-border pipeline x to balancing zone z due to supply contract f of shipper e in period p [GWh]* |
| $V_{p,i,q,e}^{DIV}$ | *Diverted volume to international market i due to supply contract f of shipper e during period p [GWh]* |
| $q_{p,r,e}^{REG}$ | *Regasified volume at regasification terminal r by shipper e in period p [GWh]* |
| $q_{p,r,e}^{LNG}$ | *Stored LNG at regasification terminal r by shipper e at the end of period p [GWh]* |
| $q_{p,s,e}^{TNK}$ | *Loaded volume into LNG road tankers at regasification terminal r by shipper e the day d [GWh]* |
| $q_{p,i,r,e}^{ULD}$ | *Unloaded LNG by shipper e from international market i at berth w of regasification terminal r the period p[GWh]* |
| $q_{p,r,e}^{SuppliedTNK}$ | *LNG supplied through bilateral contracts at regasification terminal r by shipper e in period p[GWh]* |
| $q_{p,s,e}^{WTH}$ | *Withdrawn gas volume at underground storage s by shipper e in period p [GWh]* |
| $q_{p,s,e}^{INY}$ | *Injected gas volume at underground storage s by shipper e in period p [GWh]* |
| $q_{p,x,z,e}^{IMP}$ | *Imported volume by cross-border pipeline x to balancing zone z by shipper e in period p [GWh]* |
| $q_{p,x,z,e}^{EXP}$ | *Exported volume by cross-border pipeline x to balancing zone z by shipper e in period p [GWh]* |
| $ratio_{t,e}^{OFR}$ | *Offered gas in the hub in block t by shipper e expressed as a percentage of the total demand [%]* |
| $ratio_{p,z,t,e}^{BID}$ | *Bided gas in the hub in block t by shipper e expressed as a percentage of the total demand [%]* |
| $q_{p,z,t,e}^{SLD}$ | *Sold gas from the block t of its offer curve in the hub located in the balancing zone z by shipper e in period p [GWh]* |
| $q_{p,z,t,e}^{PUR}$ | *Purchased gas from the block t of its bidding curve in the hub located in the balancing zone z by shipper e in period p[GWh]* |

# 1 Introduction

Over the last decade, gas markets have changed to a great extent. Traditionally, gas trading has been limited due to a lack of pipeline infrastructure, with high sunk investment costs, and scarce availability of liquefied natural gas (LNG) transport capacity. However, in the past years, the volume of traded natural gas in general and of LNG in particular has been growing. The BP Energy Outlook [1] states that gas will be the fastest growing traditional fuel, increasing by 1.8% a year over 2015/2030. Moreover, gas markets of practically all industrialized countries are undergoing profound structural changes brought about by governmental policies aimed at liberalizing the existing gas markets. The changing regulatory environment is leading on to a structural change in the gas industry, its trading patterns and price formation.

In Europe, the gas market situation has changed considerably with the liberalization of the gas industry and the development of the liquefaction technology that has led to the possibility of importing large amounts of LNG by vessels to Europe. Although LNG has been used since 1960s, its utilization was limited to small separate markets. However, over the last years LNG has been strongly developed. Political and economic considerations, such as the recent political unrest in the Crimea region, have led to energy security concerns about gas supplies. Importing LNG is a way to diversify gas suppliers. Thus, there is no need to rely on few external suppliers. LNG is an alternative to domestic production and pipeline import for periods with higher demand, as economies of scale for LNG continue increasing.

Regarding the liberalization of the market, the 3rd EU Gas Directive (2009/73/EC) proposes the unbundling of activities (i.e., separation of networks from activities of production and supply), the implementation of entry-exit access systems and the constitution of national or supra-national virtual hubs to enlarge the market, reduce the entry barriers and improve the degree of competition. This has led to the emergence of balancing zones and trading hubs in Europe [2]. Although these hubs appear to be liquid, a large amount of gas is still traded through long-term contracts with oil indexed prices, which normally entail restrictive clauses (e.g., Take-or-Pay (ToP) clauses) that reduce flexibility and slow down the natural gas market liberalization process. Due to the fact that entries and exits from the balancing zones may be uncertain, shippers buy and sell gas to balance their position. The competitive framework is progressively increasing the gas trade, which was formerly performed through OTC bilateral operations.

Thus, with these dynamically changing conditions in today's gas markets and the imperfect competition motivated by both economic and political issues, there is a need for natural gas models to respond to these conditions in a way that more realistically represents the individual players' behavior, and the role of information related to only partial foresight of future conditions [3]. This has led to efforts by the research community to develop decision and analysis support models adapted to the new market trends and the new regulatory changes undergoing on the EU to move towards a unique European gas market. According to [4], two main types of gas market models are found in the literature: cost minimization problems and complementarity-based equilibrium models.

There a number of previous models that have used the cost minimization approach. TIGER (Transport Infrastructure for Gas with Enhanced Resolution) model [5], [6], [7] is a cost minimization model which optimizes natural gas supply and dispatch for Europe with a very detailed representation of the physical gas infrastructure. EUGAS [8] is another cost minimization model developed to analyze future European gas supply. As a global extension of this model, the MAGELAN model [9], [10] was developed. Another cost-minimization model is the GASCOOP [11] model, which accurately captures the performance of a gas market based on an entry-exit access system. It contains a detailed representation of any entry-exit market infrastructure operation considering the influence of long-term supply contracts and LNG carrier's movement. Other example is the cost minimization model is ROM [4], a model for the UK gas market with stochastic demand used to predict prices and future gas flows and to investigate stress-test scenarios in the UK. More recently, this approach has been used to develop a perfect competition worldwide model with the focus on Europe in [12].

Regarding complementarity-based equilibrium models, as the European natural gas sector has been described as a Cournout oligopoly in the literature [13], there is a plethora of models following this approach. GASMOD [14] is a model structured as a two–stage game of successive gas exports to Europe (upstream market) and wholesale trade within Europe (downstream market) and which explicitly includes infrastructure capacities. Another model that represents the gas market through a complementary-based equilibrium problem is GASTALE (Gas Market System for Trade Analysis in a Liberalizing Europe) [15], [16] and more recently [17] with a European market focus. In [15], a successive oligopoly is modeled in which oligopolistic producers compete against each other à la Cournot. The model described in [17] extends both [15] and [16] in several important ways including the investment dynamics. Based on this model, a stochastic equilibrium model S-GASTELE [18] was developed to reflect uncertain situations of the gas market. NATGAS [19] is another European gas market model that provides long-run projections of supply, transport, storage and consumption patterns. Another model that uses this approach is the EPRG-GMM [20] model, a strategic Eurasian gas market model that represents horizontal oligopolistic relationships among producers and bilateral market power between producer (Russia) and transit (Ukraine) countries. The last reviewed European model is the GAMMES [21] model, based on an oligopolistic approach of natural gas markets. Other Nash-Cournot models are applied in the north American framework [22]–[25] and for analyzing the global gas market [26]–[30].

The approach of these gas market models diverges in the type of market structure that they try to represent. Although profit-maximizing equilibrium models are recommended due to economies of scale, the cost-minimization approach is adequate when looking for a welfare-maximizing solution. Regulators, system operators, and private companies will choose the approach that fits their specific objective. After analyzing the current state of art of gas market models, we have detected a relevant and generalized gap regarding the detailed representation of the daily gas market operation within an imperfectly competitive framework. To the best of our knowledge, no model considers the oligopolistic market structure while simultaneously and thoroughly representing operation market decisions, in particular, the daily LNG carrier arrivals.

From the reviewed literature, it can be concluded that the GASCOOP model [11] outperforms in representing the daily details of the gas market operation. In order to represent LNG vessels, GASCOOP utilizes integer variables which provides the aforementioned detailed representation of the daily operation. However, the use of integer variables is not possible in equilibrium models which are based on the MCP or bi-level approach. For this reason, the purpose of this paper is, by using GASCOOP as a starting point, to extend the algorithm developed in [31], that allows to capture the profit-maximizing behavior of one of the main agents that is involved in the gas market operation: the shipper, while maintaining the level of detail in representing the daily operation by including the representation of a market balance to analyze shippers behavior.

A key aspect of GASCOOP [11] is that each shipper participating in the market covers an inelastic demand. The model considers perfect competition without market power, as companies cannot compete for the demand. Although in this context, and according to [32] maximizing profits is equivalent to minimizing costs, the model includes constraints that link shippers' decisions, i.e., infrastructures' capacities, international markets' capacities, swaps and bilateral contracts between shippers. This causes that a minimization of costs leads to maximizing social welfare oriented decisions instead of maximizing individual profits. Therefore, in order to study the strategic behavior of a company, a maximization algorithm to solve these links was developed in [31].This algorithm allows to obtain an optimal solution in which each company looks for its individual welfare maximizing its profits. This algorithm is explained in detail in section 2.

In order to represent a gas market balance, all the counterparties have to be modeled simultaneously, because if one company decides to sell in the hub another company has to be willing to buy. As the maximization algorithm developed in [31] analyzes the shippers independently, a new algorithm is needed in order to be able to represent the interaction between companies in the hub. The algorithm developed is currently being used in one of the major natural gas companies operating in Spain to help in its medium term operation decisions.

This paper contributes to the current literature by:

- Providing a resolution method for the analysis of the strategic behavior of one of the main agents involved in the gas market: the shipper, while representing the gas market operation in detail.
- Representing the market balance (hub) in order to analyze real market operations that shippers have to face in their decision-making process to solve the common resource constraints.
- Analyzing the impact of introducing a hub in the downstream natural gas market.
- Development and validation of the results with a simplified case study based in MIBGAS.

The remainder of the paper is organized as follows. In section 2, we describe the maximization algorithm developed in [31] to capture the shippers' profit-maximizing behavior, which is the starting point of this paper. In section 3, we present the algorithm developed to include the influence of a natural gas hub which is illustrated in section 4 with a case study and compered with the maximization approach without a market balance. In section 5, the outcomes of the study are discussed and conclusions are drawn.

# 2 Maximization algorithm

In this section the maximization algorithm developed in [31] to solve the problem of common resource constraints is explained in detail. This algorithm reproduces the most common decision-taking process in two phases (Figure 1) when a shipper is determining its market operation decisions. In the first phase, each of the shippers individually maximizes its profits as if no other party exists in the gas market. Hence, each company makes its decisions considering that the facilities' total capacity is available for them. In this phase, the decisions that link the different shippers have to be determined in order to maximize shipper's profits individually. The main decisions that link companies are due to bilateral contracts, because one of the main features of this type of contracts is the priority of the gas demand related to the supplied companies. Thus, this has to be taken into account in this phase where each company takes its decisions unilaterally, because suppliers have the obligation to deliver the natural gas that the supplied companies require. The second phase is solved from the point of view of the system operator. Shippers refer their decisions to the system operator, who allocates the capacity to the shippers while minimizing total system costs by solving the constraints related to infrastructure capacities, international market capacities and swaps.

Because this second phase may modify the initial individual decisions, the model is iteratively solved until convergence is reached. The convergence condition is that the individual profits do not change between two consecutive iterations. When this happens, the decision variables are fixed. If the companies' decisions do not exceed the infrastructure limits, there is no need to solve again phase 1. It has been tested with real cases of the detailed MIBGAS system and the model's running time ranges between five and ten minutes on a 64-bit PC and takes between two or three iterations to reach the convergence.

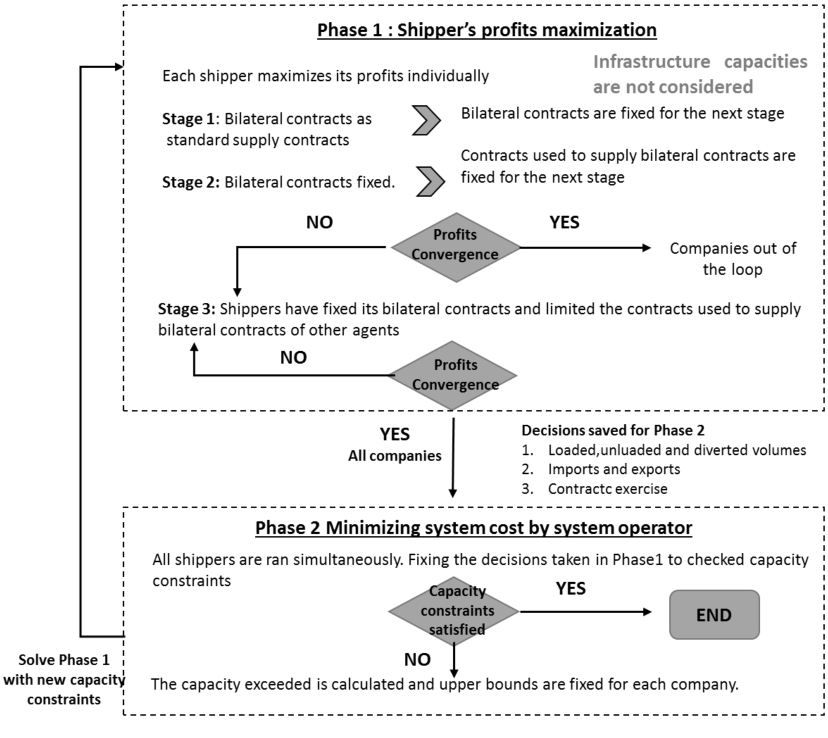

**Figure 2-1: Profits maximization algorithm**

In the first phase, where each shipper is individually modeled, GASCOOP [11] model can be used for maximizing their profits. This model considers perfect competition without market power and, under in this conditions maximizing profits is equivalent to minimizing costs [32]. However, GASCOOP [11] includes constraints that link the shippers' decisions, i.e. bilateral contracts and international markets. These forces to solve the links regarding the bilateral contracts between shippers and international markets, so these decisions are led by the maximum individual profit and not by the maximum social welfare.

Of these constraints, the first one is a maximum condition and the second ones deals with the priority among companies. Regarding the maximum condition, the maximization algorithm of GASCOOP model assumes, as initial hypothesis that a priority order based on market share is capable of modeling the access of each agent to spot markets. Shippers take their decisions assuming they can only use the residual liquidity not used by shippers with greater priority. Therefore, agents with priority in the markets would be in the best position, this is, they would maximize their profits more.

This approach, works in markets with a structure of a market leader and several followers such as the Spanish market, which is the focus for the development of this model. Therefore, this priority order is an input data for the model that must be calibrated based on the results of the model and market experience.

Regarding bilateral contracts, this type of contract is a consequence of the opening of natural gas markets to competition. Since that moment, some incumbent companies became suppliers of newcomers through bilateral supply contracts. Therefore, and although in general only incumbent companies become suppliers of newcomers through new supply, it is possible to distinguish four types of companies depending on their relationship with bilateral contracts as shown in Figure 2-2.

1) Companies without any bilateral contracts; 2) companies who are suppliers to other companies; 3) companies that are suppliers for some companies, and at the same time are supplied by others; 4) companies who are supplied by others.

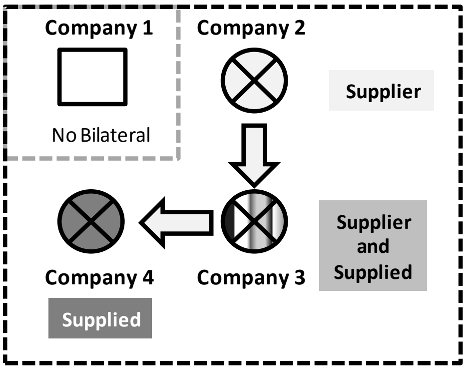

**Figure 2-2: Types of companies by bilateral contracts** [31]

In order to represent the strategic behavior of companies involved in bilateral contracts, it is necessary to solve the decisions of the supplied companies first, which have the right to decide the amount of gas supplied to them by this type of contracts and then send this information to the suppliers that have to take this obligation into account.

An iterative algorithm in which supplied companies decide and then their decisions are fixed and established as an obligation to suppliers was developed to represent this process. The companies whose benefits do not change between two consecutive stages are excluded from the algorithm and their decisions are kept for the second phase where the capacity is allocated to the shippers by the system operator, taking into account the decisions made in this first phase.

After solving the stages of the first phase, once no company change their profits between two consecutive stages, the decisions made by each shipper are kept for solving the next phase of the algorithm (Phase 2), this is: a) Loaded, unloaded and diverted volumes; b) Imports and exports; and c) Supply contracts exercise.

The second phase is solved from the point of view of the system operator. The objective of this phase is to allocate the capacity while minimizing the total system costs and taking into account the decisions made by the shippers in Phase 1. In this phase the limits of the main infrastructures are checked and shippers are asked to change their decisions in order to fulfill capacity limits.

The system operator has to check if the sum of the total utilization of infrastructures decided by the shippers in Phase 1 exceeds their maximum capacity. If the sum of the total use by all agents is greater than the infrastructure capacity, upper bounds for each shipper are established in the corresponding infrastructure to avoid unfulfillment capacity constraints. These upper bounds are calculated as the use of each infrastructure by each shipper minus the value of the capacity exceeded prorated by the use of each facility. Therefore, if capacity limits are not fulfilled, Phase 1 should be run again with new capacity constrains to limit the use of the infrastructure to the previously calculated upper bounds.

In order to avoid establishing upper bounds that companies cannot fulfill due to their requirements, auxiliary slack variables are used in each individual shipper's optimization problems of Phase 1. If any auxiliary slack variable is activated, the upper bounds per shipper and infrastructure are recalculated in Phase 2, adding to the shippers upper limits whose slack variable has been activated this amount of surplus capacity, which will be subtracted from the rest of companies prorated. With the new calculated upper bounds Phase 1 will be run again. Once the System Operator is satisfied, i.e., no slack variable is activated, the final solution is obtained.

# 3 Market balance implementation

The European regulation (No 715/2009) included in the 3rd EU Gas Directive (2009/73/EC) require the state members to develop a natural gas market balance model based on a wholesale market, where all companies can compete clearing bids to sell and buy gas, in order to achieve a more transparent and agile market. Traditionally, natural gas markets were ruled by bilateral contracts, implementing a balancing market increases interactions among the agents, who will balance their positions by selling and buying gas in the market.

Representing the balancing market (hub) and thus the interaction between the agents with the maximization algorithm explained in the previous section is not possible. Companies maximize its benefits unilaterally, considering that the facilities' total capacity is available for them and that no other companies operate in the system. Therefore, there is no counterparty for the decisions made by each agent. If there is company willing to sell in the hub, another company has to be willing to purchase, and within this algorithm a counterparty is not represented in each company's problem.

Thus, in order to represent the Hub the maximization algorithm [31] has been completed with a new phase that allows to represent a market balance while maximizing each agent's profits individually and keeping the accurate representation of the daily operation.

The approach developed to include the balancing market in the maximization model involves including a new phase in the maximization resolution algorithm (Figure 3-1). After the maximization algorithm, this new phase (Phase 3) is carried out in order to calculate the bidding curves for each of the shippers. As a result of the bids clearing, the model obtains the traded volumes in the hub by each shipper as well as the hub price. After this phase, the maximization problem has to be solved again, but taking into account the decisions made in Phase 3. Thus, the two phases of the maximization algorithm are solved again but changing the shippers' demand according to the gas sold or bought in the hub to obtain the final decisions of the shippers. Because sales and purchases in the hub change the operation of the system it is needed to recalculate shippers' decisions to reallocate the transactions among companies in the hub.

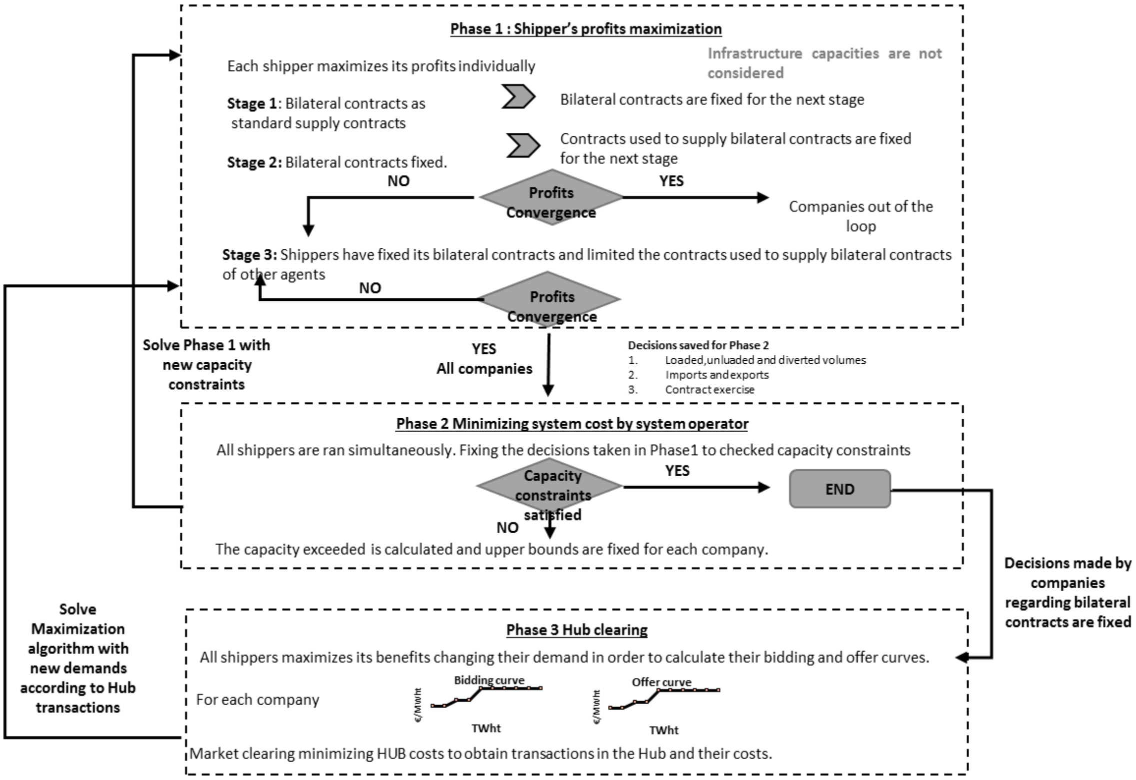

**Figure 3-1: New algorithm for representing the market balance**

The market clearing is divided into two stages. In the first one, the offer and bid curves for each shipper are calculated, and in the second stage, the market is cleared.

The offer and bid curves of each shipper are divided into blocks of natural gas quantities. In order to calculate the offer and bidding price for each block, the demand of each shipper is increased for the offer curves and decreased for the bidding curves to calculate the marginal costs of these increases and decreases by maximizing each shipper's profits.

Purchases on spot markets made to offer in the hub by one shipper will affect the rest of the shippers due to the limited liquidity of the markets. In addition, the use of the infrastructures will change depending on the transactions of each shipper in the hub and may affect other shippers' decisions. It is not possible to know the amount of gas cleared in the hub beforehand. Therefore, when calculating the shippers' bidding curves, we take as starting point the results obtained from the maximization algorithm, where each shipper maximizes its benefits covering its initial demand. This is, for the calculations the rest of the shippers are assumed to not to change their initial positions fixing their decisions to the results obtained in the maximization phase. This has been proved to be the most efficient solution, as purchases and sales in the hub are mostly for balancing decisions. Thus, companies' positions after clearing the hub will be close to the decisions made without a market balance.

Decisions made by companies supplied through bilateral contracts may also affect the bidding curves of the suppliers because their decisions are linked as explained in section 2. Therefore, the model will have to take into account the decisions of the supplied companies to calculate the suppliers' bidding curves. As it is not possible to know beforehand the gas cleared by supplied companies, we have reach a compromise between precision of the algorithm and execution time, assuming that the exercise of bilateral contracts is the obtained from the maximization algorithm; this is without participating in the hub.

The resolution of bilateral contracts would require more iterations and presents convergence problems. After clearing the market with this first assumption, it would be necessary to recalculate the bidding curves for each company involved in bilateral contracts taking into account the volume cleared by supplied companies and their bilateral contracts exercise and repeat the market clearing iteratively. This situation could not reach convergence.

Furthermore, assuming that gas supplied through bilateral contracts cannot be used to make offers in the hub is close to the real operation, as supplied companies cannot exert their bilateral contracts in such a small time horizon to participate in the daily operation of the hub.

To do this, for this phase, bilateral contracts' volumes are fixed when calculating the curves of companies supplied by them, and the volume available to the companies that have to supply through this type of contracts is limited for the calculation of its bidding and offer curves. In order to give these signals to the model, the starting point for the calculations will be the results obtained from phase two of the maximization algorithm; this is, without participating in the hub. Supplied gas through bilateral contracts is considered as an obligation for the suppliers that will not be able to use that gas for another purpose (2) and the requested gas by supplied companies is fixed (1).

$$V_{p,q,e}^{Total} = V_{p,q,e}^{Bilateral} \quad \forall p,q,e \tag{1}$$

$$V^{Total}_{p,q,e} = \sum_{i,r} V^{MET}_{p,i,r,q,e} + \sum_{x,z} V^{IMP}_{p,x,z,q,e} + \sum_{i} V^{DIV}_{p,i,q,e} + \sum_{q',e'} V^{Supplied}_{p,q',e',q,e} \quad \forall p,q,e \tag{2}$$

$$V^{Bilateral}_{p,q,e} = V^{Supplied}_{p,q',e',q,e} \quad \forall p,q,q',e,e' \tag{3}$$

The bilateral contracts delivered in LNG tanks do not have an associated supply contract (The supply company can deliver the gas in the regasification tank to the supplied company from one or more supply contracts, but also from a physical swap with other companies or from surplus gas stored in the tank). Thus, for these contracts, the supplied volume cannot be established as an obligation from a contract of the supplier as done for the rest of the bilateral contracts (2). Instead, the obligation to supply this gas is introduced in the balance equation of the corresponding regasification plant for the supplier.

$$q^{LNG}_{p,r,e} - q^{LNG}_{(p-1),r,e} = \sum_{i'} q^{ULD}_{p,i,r,e} - q^{REG}_{p,r,e} - q^{TNK}_{p,r,e} - q^{SuppliedTNK}_{p,r,e} \quad \forall p,i,r,e \tag{4}$$

Lastly, the diverted volumes have also to be fixed for the supply companies in order to keep their position as well as for the suppled companies.

$$\sum_{i} V^{DIV}_{p,i,q,e} + \sum_{i'} V^{DIV}_{p,i,q',e' \subset V^{Supplied}_{p,q',e',q,e}} \leq \overline{V}^{DIV}_{p,q,e} \quad \forall p,q,e,q',e' \tag{5}$$

$$V^{DIV}_{p,i,q,e} = V^{Bilateral}_{p,i,q,e} \quad \forall p,i,q,e \tag{6}$$

Once the bilateral contracts have been fixed, all the agents can be modeled independently with no need to repeat the different stages of the maximization algorithm’s phase 2, as companies will not change their benefits because volumes delivered by bilateral contracts are fixed. Thus, it is enough to solve the stage 3, from the first phase of the maximization algorithm, to calculate the price of the bidding and offer blocks for each shipper.

For the calculation of the bidding curves, the number of gas quantity blocks can be defined per shipper for the purchases and sales curves as well as the percentage of the demand of each bidding or offer block.

The price for each block of the offer curve is obtained for each shipper as the dual variable of its gas balance equation in the balancing zone where the hub is placed, increasing its demand by the quantity of the corresponding block.

$$\sum_{r} q^{REG}_{p,r,e} + \sum_{s}\left(q^{WTH}_{p,s,e} - q^{INY}_{p,s,e}\right) + \sum_{x}\left(q^{IMP}_{p,x,z,e} - q^{EXP}_{p,x,z,e}\right) = (1 + \mathrm{ratio}^{OFR}_{t,e} + \sum_{t' \leq t} ratio^{OFR}_{t,e}) \cdot D^{TOT}_{p,z,e} \tag{7} \quad : \mu_{p,z,e,t}$$

By using this approach, we obtain increasing marginal costs in each quantity block for all the shippers. An example of a company with 10 offer blocks of 5% of its demand each one is shown in Figure 3-2.

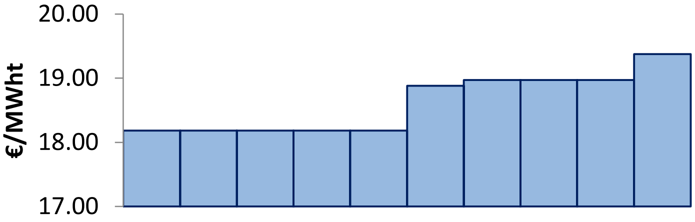

**Figure 3-2: Offer curve in quantity blocks**

The curve of all the shippers is then linearized in order to include it in the objective function for the market clearing. The obtained points are joined by straight lines whose equation is $y = m \cdot x + n$. Thus, it is necessary to calculate the slope and the y-intercept of each segment. The calculation of the bidding curve is carried out in the same way but decreasing the shippers demand instead of increasing it.

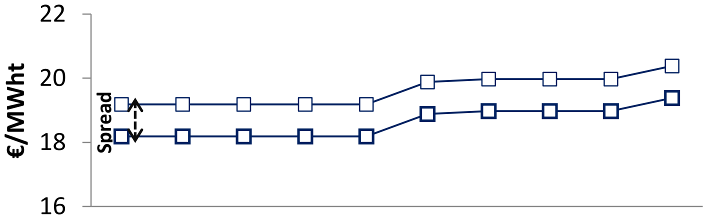

**Figure 3-3: Linearized offer curve**

The first point for the offer and bidding curve of each of the shippers is the marginal cost obtained from the maximization algorithm. This is the cost that will be obtained without participating in the hub, and thus, without sales nor purchases in the hub.

A spread for the offer curves has been added in order to reflect the benefits derived from participating in the hub, otherwise if the shippers offer and bid their marginal costs their profits will not change with the participation in the Hub. This spread also reflects the effect of the other companies in the shipper’s costs. As mentioned previously, for the calculation of the curves the rest of the shippers are supposed to maintain their position, thus the real marginal cost could be slightly different than the calculated, depending on the other shippers’ decisions.

$$Int^{OFR}_{p,z,e,t} = Int^{OFR}_{p,z,e,t} + Spr^{OFR}_{p,z,e} \quad \forall p,z,e,t \tag{8}$$

$$Int^{BID}_{p,z,e,t} = Int^{BID}_{p,z,e,t} + Spr^{BID}_{p,z,e} \quad \forall p,z,e,t \tag{9}$$

Once the offer and demand curves for every shipper participating in the market have been calculated, they are linearized and the curves’ clearing is simulated, minimizing the total cost of the transactions in the hub, which is equivalent to maximizing the transactions’ utility. This implies solving a quadratic problem .

$$Min\left[\begin{array}{l}\sum_{p,z,t,e} q_{p,z,t,e}^{SLD}\cdot\left(q_{p,z,t,e}^{SLD}\cdot\frac{Slp_{p,z,e,t}^{OFR}}{2}+Int_{p,z,e,t}^{OFR}\right)-\\ \sum_{p,z,t,e} q_{p,z,t,e}^{PUR}\cdot\left(q_{p,z,t,e}^{PUR}\cdot\frac{Slp_{p,z,e,t}^{BID}}{2}+Int_{p,z,e,t}^{BID}\right)\end{array}\right] \qquad (10)$$

The problem is subject to the following constraints, this is, that the total purchases have to be equal to the total sales in the hub, and bearing in mind that the purchases and sales of each company have to be coherent with their bidding curves.

$$\sum_{t,e} q_{p,z,t,e}^{SLD} = \sum_{t,e} q_{p,z,t,e}^{PUR} \quad \forall p,z \qquad (11)$$

$$q_{p,z,t,e}^{SLD} \leq q_{t,e}^{OFR}\cdot D_{p,z,e}^{TOT} \quad \forall p,z,t,e \qquad (11)$$

$$q_{p,z,t,e}^{PUR} \leq q_{t,e}^{BID}\cdot D_{p,z,e}^{TOT} \quad \forall p,z,t,e \qquad (12)$$

From the market clearing, we obtain the volumes negotiated in the hub and the bid, mid and ask prices in the hub. After this phase, the maximization algorithm has to be solved again, taking into account the decisions made in this new phase. Thus, the two phases of the maximization algorithm are solved by changing the shippers demand according to the volumes negotiated in the hub. The shippers that have bought in the hub in phase 3 will reduce their demand by this amount, whereas the ones that have sold will increase their demand.

## 4 Case study

The model is under operation in one of the biggest companies operating in the natural gas market in Spain and has been tested with real data and a complete representation of the MIBGAS system. However, as the main intention of this paper is to show the effect of introducing competition and establishing a virtual gas hub, the case study presented here is a simplification of MIBGAS physical and market structure. The system has been simplified reducing the number of available infrastructures and the spot markets for natural gas and LNG.

The main considerations regarding the physical and market structure considered in the case study (Figure 4-1) are the following:

- A unique market area constituted as one balancing zone is considered for the study.
- Two regasification terminals are considered in MIBGAS (REG1 and REG2).
- One large storage facility is considered (MIB1).
- MIBGAS is connected through cross-border pipelines to the NG1 and NG2 natural gas markets.

- Four LNG markets are considered, two for LNG supply (LNG1 and LNG2) and two for diverting natural gas. LNG (DIV1 and DIV2).

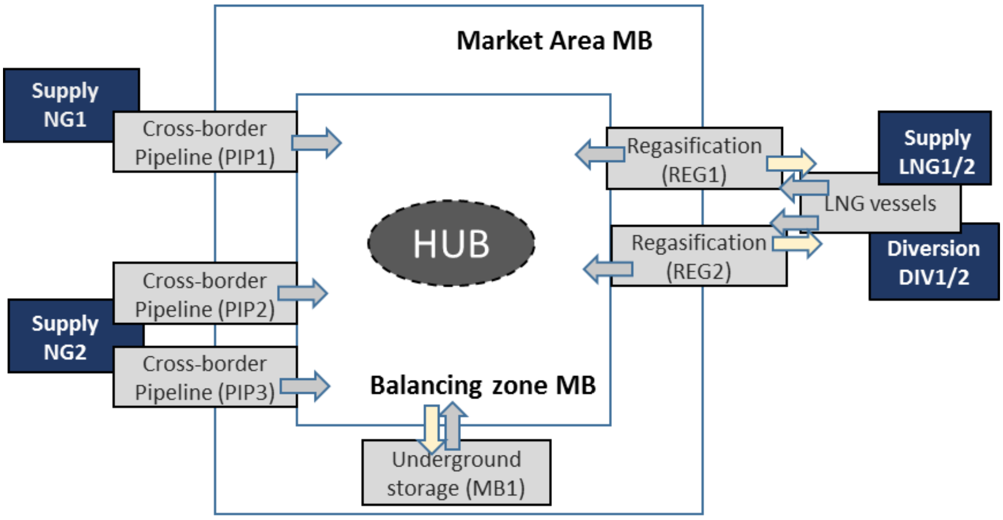

Figure 4-1: Market structure

For the sake of clarity, we have considered a gas system with three shippers who have signed upstream long-term contracts and buy gas in the spot markets to supply their demands during a three-time-period scope. The shippers have also the possibility to divert LNG to the markets to increase their profits.

The problem is formulated as a MIP and has been implemented in the GAMS language and solved by using CPLEX optimization software [33].

## 4.1 Case description

Each shipper owns a long-term contract portfolio (Table 4-1) to supply an inelastic demand (Figure 4-2) and can also participate in the natural gas and LNG global markets. The parameters that define the global markets are shown in (Table 4-2).

| Shipper | Contract by market of origin | Max. Volume (GWh) | Max. diverted volume (GWh) | Average price (€/MWh) | Commercial rules |
|---|---|---|---|---|---|
| E1 | NG2 (Tarifa) | 25,775 | - | 18.75 | - |
| | LNG1 | 28,491 | 28,491 | 18.28 | FOB |
| | LNG2 | 2,706 | 2,706 | 18.85 | FOB |
| E2 | LNG2 | 15,980 | 15,980 | 17.93 | FOB |
| | NG2(Medgaz) | 5,815 | - | 20.70 | - |
| | NG2(Tarifa) | 909 | - | 19.35 | - |
| E3 | NG2(Medgaz) | 10,093 | - | 21.53 | - |
| | LNG1 | 8,186 | 8,186 | 18.88 | FOB |
| | Delivered in tank | 1,854 | - | 21.95 | - |

Table 4-1: Long-term Contract Portfolio

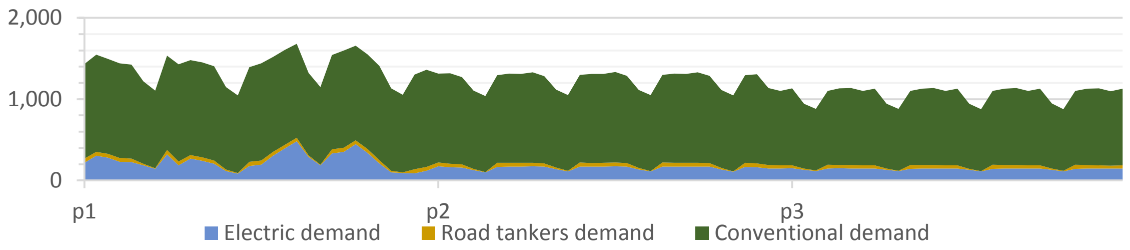

**Figure 4-2 Natural gas demand (GWh)**

| Period | Natural gas supply markets | | | | LNG supply markets | | | | LNG markets for divertions | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | NG1 | | NG2 | | LNG1 | | LNG2 | | DIV1 | | DIV2 | |
| | Price | Capacity | Price | Capacity | Price | Capacity | Price | Capacity | Price | Capacity | Price | Capacity |
| | *€/MWh* | *GWh* | *€/MWh* | *GWh* | *€/MWh* | *GWh* | *€/MWh* | *GWh* | *€/MWh* | *GWh* | *€/MWh* | *GWh* |
| p1 | 18.03 | - | 14.65 | - | 25.79 | 74,874 | 20.64 | 15,706 | 30.94 | 4,840 | 20.86 | 11,616 |
| p2 | 19.61 | - | 14.714 | - | 25.24 | 74,874 | 20.19 | 15,706 | 30.30 | 4,840 | 22.25 | 11,616 |
| p3 | 18.93 | - | 14.779 | - | 19.58 | 74,874 | 15.65 | 15,706 | 23.50 | 4,840 | 20.64 | 11,616 |

**Table 4-2 Sport markets capacities and prices**

The model determines the natural gas entries to MIBGAS, LNG carrier arrivals and imports, together with inventory variations (LNG in tanks, gas in storage facilities and line-pack capacity), in order to cover shippers' demand and diverted volumes by optimizing the shippers' management of gas supply contracts and the purchases and sells in the international markets.

The spread considered for the offer curves of the three shippers modeled is 1 €/MWh in order to maintain the gas hub price reasonable with the hub prices in Spain [34]. Shipper E1 covers approximately the 80% of the demand, E2 covers 15% and E3 covers the remaining 3% of the demand. Thus, E1 is the company that has priority in the spot markets followed by E2 and E3.

In Appendix 1, the technical characteristics of the modeled infrastructures and the tariffs applied to its use are described in detail.

## 4.2 Results

The algorithm described in this paper has been applied to the case study (detailed in the previous subsection) and the results have been compared with the ones obtained using the profit maximization perspective without a market balance and the cost minimization approach. The problem solved for the system operator consist of 4,255 equations and 7,121 variables and the problem solved for each of the shippers is comprised of 3,534 equations and 7,083 variables.

The minimization of costs leads to maximizing social welfare. Thus, in this approach, the costs of the system are the least possible while covering the demand (Figure 4-3). The diverted volumes in this approach are decided seeking the welfare of the system. Therefore, as E2 has the cheapest LNG contract (Table 4-1), the model diverts this contract making the profit of E2 increase with respect to the maximization approach ( Figure 4-4). In the maximization approach, company E1 has priority in the spot markets. Thus, this company diverts to the market with a higher opportunity cost, blocking the diversions form E2 ( Table 4-3), whose profits decrease. In the maximization approach, the margin of the small companies is lower as they are affected by the biggest company that increases its profits using the spot and diversion markets without taking into account the rest of the system ( Figure 4-4).

When the market balance is introduced, the impact of the decisions made by E1 in the other shippers' profits is stronger. As this company sells in the hub, it has to increase its gas supply. Therefore, this shipper, that has priority in the spot markets, takes over the cheapest spot LNG market. This forces shipper E2 to supply part of its demand using long-term contracts instead of buying in the spot market LNG1, which is cheaper, as now has to reduce its purchases in it due to the limited liquidity of the market ( Table 4-3). Even if a shipper does not participate in the hub, their profits will be affected by the participation of agents with more market power if capacity or market's liquidity constraints are activated. Shipper E3 increases its profits with the introduction of the hub, by buying gas from E1 that has a cheaper supply cost.

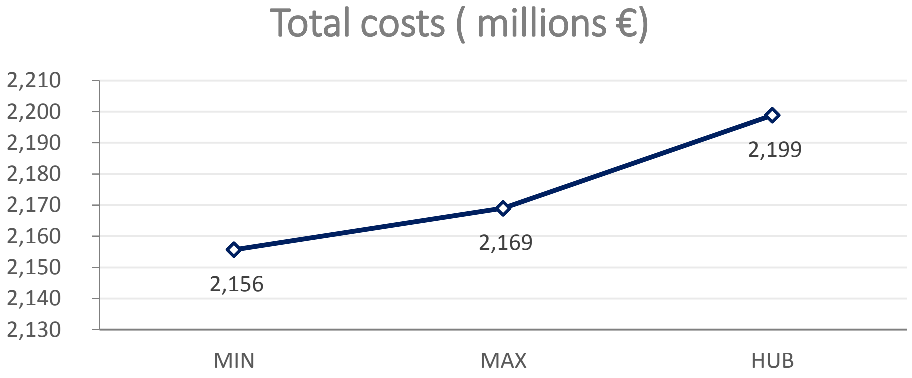

**Figure 4-3: Total system costs**

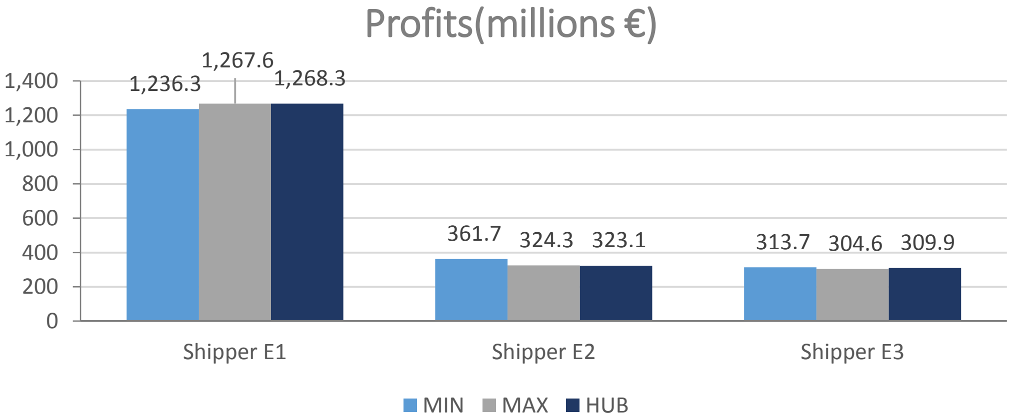

**Figure 4-4: Shippers' profits**

| *Period* | *Shipper* | *Contract exercise* | *NG Spot Purchases* | *LNG Spot Purchases* | *Diverted volume* |
|---|---|---|---|---|---|
| E1 | Min. | ⬇ | ➡ | ⬇ | ⬇ |
| | Max. | ⬆ | ➡ | ⬆ | ⬆ |
| | Hub | ⬆ | ➡ | ⬆ | ⬆ |
| E2 | Min. | ⬆ | - | ⬇ | ⬆ |
| | Max. | ⬇ | - | ⬆ | ⬇ |
| | Hub | ⬆ | - | ⬇ | ⬇ |
| E3 | Min. | ⬇ | - | ⬆ | - |
| | Max. | ⬆ | - | ⬇ | - |
| | Hub | ⬇ | - | ⬇ | - |

**Table 4-3: Shippers' operational decisions**

The marginal costs for each shipper, in both the minimization and the maximization approach, are shown in Table 4-4 as well as the volume sold and purchased by each shipper. When seeking the welfare of the system, the marginal costs of the three shippers are more similar and the small companies benefit at the expenses of the shipper with more market share. In the profit maximization approach, the shipper with more market power reduces its marginal costs by using the spot and diverted markets prior to the rest of the shippers. Shippers E2 and E3 have to use more expensive contracts to cover their demand because shipper E1 hoards the most profitable markets.

| *Period* | *Shipper* | *Marginal Cost Min. (€/MWh)* | *Marginal Cost Max. (€/MWh)* | *Volume sold (€/MWh)* | *Volume purchased (€/MWh)* |
|---|---|---|---|---|---|
| p1 | E1 | 22.51 | 20.08 ⬇ | 700.87 | - |
| | E2 | 22.32 | 22.49 ⬇ | 51.59 | - |
| | E3 | 22.7 | 23.45 ⬆ | - | 752.46 |
| p2 | E1 | 22.14 | 20.49 ⬇ | 397.61 | - |
| | E2 | 21.96 | 22.9 ⬆ | - | 145.88 |
| | E3 | 22.14 | 22.76 ⬆ | - | 251.73 |
| p3 | E1 | 21.6 | 19.47 ⬇ | 353.75 | - |
| | E2 | 21.6 | 21.94 ⬆ | - | 103.37 |
| | E3 | 20.8 | 21.68 ⬆ | - | 250.38 |

**Table 4-4: Shippers' marginal costs**

The volume traded in the hub as well as the clearing price are shown in Table 4-5. The volume traded in the hub is residual, as companies only use it for balancing purposes. The hub clearing price is between the marginal costs of the shippers, selling gas shippers with lower marginal cost and buying the ones that have a higher marginal cost (Table 4-4).

| *Period* | *Hub Price*<br>*(€/MWh)* | *Volume negotiated*<br>*(GWh)* |
|---|---|---|
| p1 | 22.53 | 1504.92 |
| p2 | 22.18 | 795.22 |
| p2 | 21 | 707.49 |

**Table 4-5: Hub transactions**

The offer curve for shipper E1 is shown in Figure 4-5 for period p1. The initial point of the curve is the shipper's marginal cost for the maximization approach plus the established spread. In this period, shipper E1 sells gas to shipper E3 whose bidding curve is shown in Figure 4-6. Shipper E2 has a marginal participation in the hub as its marginal cost in the maximization approach (Table 4-4), and thus without participating in the hub, is really close to the clearing price in this period.

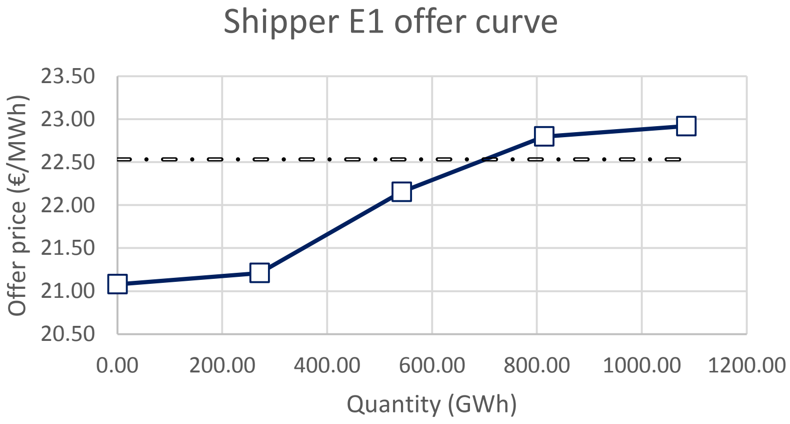

**Figure 4-5: Shipper E1 offer curve in period p1**

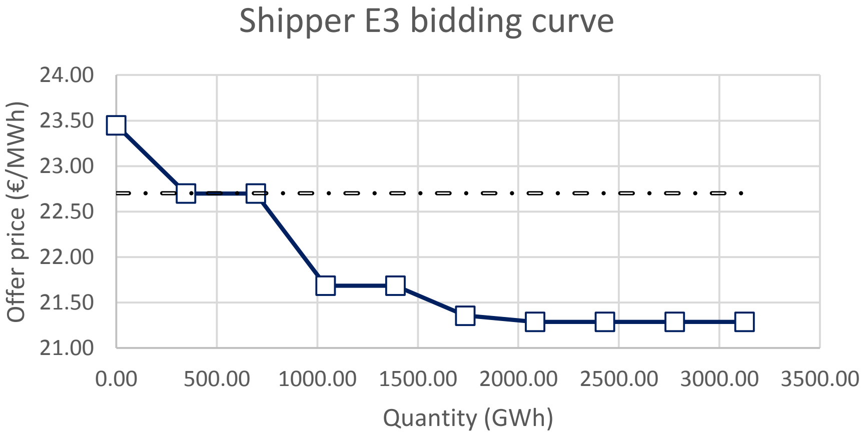

**Figure 4-6: Shipper E3 bidding curve in period p1**

In 2016, approximately a 2% of the demand was traded in MIBGAS [35], which is coherent with the obtained results of this work's proposed model. In our case study the volume negotiated in the hub is between 2% and 3% of the total demand. Most of the demand is still supplied by long-term contracts and the transactions in the hub are carried out mostly to balance the agents' positions. Shippers E2 and E3 can cover their whole demand with their contract portfolio, using the spot markets to reduce their costs if there is available liquidity and the market balance if it is profitable. Shipper E1 has to buy gas in the NG spot market, as their supply contracts do not cover its needs. As this company has priority in the markets, it benefits from lower prices in the spots markets and higher opportunity costs in the diverted markets when maximizing shippers' benefits instead of looking for the welfare of the system. In addition, due to this advantage, this company participates in the market balance selling gas to small companies that cannot benefit of spot markets due to the lack of liquidity.

# 5 Conclusions

The third EU Gas Directive (2009/73/EC) proposes the constitution of national or supra-national virtual hubs to enlarge the market. This has led to the emergence of trading hubs in Europe. In Spain, the natural gas hub was constituted in December 2015 and it is still very illiquid. However, the CNMC is evaluating different alternatives to increase the liquidity of the market by forcing the dominant companies to participate in the market in order to generate liquidity [35]. Therefore, it is of strategic interest to analyze the influence of a hub in the current Spanish gas market.

The main contribution of this paper is the development of an algorithm for the analysis of an entry/exit framework from different approaches studying the differences between a minimization approach and a profit maximization approach with and without a market balance.

To do this, taking as starting point the algorithm developed to maximize shippers' profits in [31], a new algorithm has been developed to introduce the effect of a market balance. This algorithm calculates the offer and bidding curves for each shipper decreasing and increasing respectively their demand and calculates the marginal costs due to these increases by maximizing its profits and assuming the rest of the system to remain constant. Once the curves have been calculated for all the shippers, the hub is cleared and the whole system is solved taking into account the purchases and sales for each shipper in the hub using the algorithm developed in [31] to allocate the new decisions made by the shippers.

The introduction of the market balance emphasizes the effect of the companies with more market power over the smaller ones due to the market configuration modelled in which incumbent companies have priority to the markets. The maximization approach enables to analyze the effect of the power market exercise. The companies that can access spot markets prior to the others can increase their profits and take over the markets, preventing smaller companies to benefit from low spot prices and high opportunity costs in the diversion markets. With the introduction of the market balance, bigger shippers that have priority in the markets and thus can offer the best prices in the hub will participate by selling gas. Small companies may benefit by buying cheaper gas in the hub and thus reducing costs. However, this may have a negative effect on medium sized companies that cannot compete with the offers of bigger companies and thus they will not participate in the market, but will still vary their profits with respect the maximization approach due to the impact of the sales in the Hub from companies with priority in the markets. Even if a company does not participate in the hub, their expected costs may change due to other companies' decisions if they take over a spot market to sell gas in the hub that previously had enough liquidity or takes over an infrastructure.

Further research considering elasticity in the spot markets, trying to represent each market closer to reality and price elasticity of demand, which measures the responsiveness of gas demand to a change in a substitute good price, could be addressed.

Finally, another implementation of our model that could be addressed in future research are different mechanism to increase the hub liquidity, such as forcing companies with great market share to trade a percentage of their demand in the hub.

# 6 **Appendix 1**

This section contains the technical characteristics of the infrastructures considered in the model and the tariffs applied for its use.

## 6.1 **Cross-border pipelines**

| *Cross-border pipeline* | *Flow direction* | *Capacity (GWh/day)* |
|---|---|---|
| PIP2 | NG2 --> MB | 450 |
| PIP3 | NG2 --> MB | 266 |
| PIP1 | NG1 --> MB | 175 |

**Table 6-1: Cross-border pipelines characteristics**

| *Cross-border pipeline* | *Flow direction* | *Fixed tariff (€/(GWh/day))* | *Variable tariff (€/GWh)* |
|---|---|---|---|
| PIP2 | NG2 --> MB | 10,848 | - |
| PIP3 | NG2 --> MB | 10,848 | - |
| PIP1 | NG1 --> MB | 10,848 | - |

**Table 6-2: Cross-border pipelines tariffs**

## 6.2 **Regasification terminals**

| *LNG Regasification terminal* | *Berths (#)* | *Berth capacity (up to GWh)* | *Regasification capacity (GWh/day)* | *LNG Storage working capacity (GWh)* |
|---|---|---|---|---|
| REG1 | 5 | 968; 1500x3;3000 | 1,417.00 | 16510.1 |
| REG2 | 3 | 968; 1500x2 | 754.00 | 7569.8 |

**Table 6-3: Regasification terminals characteristics**

| *LNG Regasification terminal* | *Slot assignment (€/LNG carrier)* | *Unloading service (€/GWh)* | *Regasification service -fixed tariff- (€/(GWh/day))* | *Regasification service - variable tariff- (€/GWh)* | *LNG storage service (€/(GWh/day))* | *Loading road tankers -fixed tariff- (€/(GWh/day))* | *Loading road tanker-variable tariff- (€/GWh)* |
|---|---|---|---|---|---|---|---|
| REG1 | 16988 | 35 | 19,612.00 | 116 | 32.4 | 28806 | 171 |
| REG2 | 13590.4 | 28 | 15,689.60 | 92.8 | 25.92 | 23044.8 | 137 |

**Table 6-4: Regasification terminals tariffs**

## 6.3 Underground storage

| *Underground Storage* | *Working gas capacity (GWh)* | *Injection rate(GWh/day)* | *Injection slope (GWh/day/ inventory in %)* | *Withdrawal rate(GWh/day)* | *Withdrawal slope (GWh/day/ inventory in %)* |
|---|---|---|---|---|---|
| MB1 | 33832.36 | 462.459 | 3 | 410.477 | 262 |

**Table 6-5: Underground storage characteristics**

| *Underground Storage* | *Storage service -fixed tariff- (€/(GWh/month))* | *Injection service (€/GWh)* | *Withdrawal service (€/GWh)* |
|---|---|---|---|
| MB1 | 411 | 244 | 131 |

**Table 6-6: Underground storage tariffs**

## 6.4 Balancing zone

| *Balancing zone* | *Entry capacity (regasification)* | | *Exit capacity (conv. demand)* | | *Exit capacity (GFPP demand)* | | *Exit capacity (Road tankers demand)* | |
|---|---|---|---|---|---|---|---|---|
| | *-fixed tariff- (€/(GWh/day))* | *-variable tariff- (€/GWh)* | *-fixed tariff- (€/(GWh/day))* | *-variable tariff- (€/GWh)* | *-fixed tariff- (€/(GWh/day))* | *-variable tariff- (€/GWh)* | *-fixed tariff- (€/(GWh/day))* | *-variable tariff- (€/GWh)* |
| MIBGAS | 10848 | 0 | 44971 | 1249 | 30875 | 682 | 68683 | 1540 |

**Table 6-7: Balancing zone characteristics**

| *Balancing zone* | *Line-pack capacity (GWh)* | *Initial inventory (GWh)* | *Final inventory (GWh)* |
|---|---|---|---|
| MIBGAS | 450 | 0 | 0 |

**Table 6-8: Balancing zone tariffs**

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