Gas transport networks: Entry-exit tariffs via least squares methodology ☆

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Abstract

Following some of the directives and regulations in the 3rd EU Energy Package, many of the EU members are reconsidering their methodologies to derive the tariffs charged for access and usage of their gas transport systems.

Among these methodologies, the use of entry-exit tariffs computed via least squares has received the most attention over the last few years and there is a wide consensus towards the application of this approach.

The main contribution of this paper is to raise awareness on the fact that, even after a given methodology has been chosen, there are still important details to be fixed before the final tariffs are computed. Within the context of the least squares methodology we argue that, although many of these details may seem minor, they can have a big impact on the final outcome.

The paper also presents proposals on how these details can be handled while still pursuing the goals set by the EU; goals such as being transparent, cost-reflective, and non-discriminatory.

Finally, the paper concludes with an illustration of the discussed proposals, applying them to the Spanish gas transport network.

Keywords: gas networks, entry-exit tariffs, least squares

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1. Introduction

The 3rd EU Energy Package, which entered into force in 2009, has as its main objectives to open up the gas and electricity markets in the European Union and move forward towards the goals of the *Europe 2020 Strategy* through a secure, competitive, and sustainable supply of energy to the economy and the society. One of the main advantages of the liberalization of the national gas markets in Europe is to favor competition, which would lead to lower prices, higher volume of trades and, ultimately, to higher welfare for the final consumer. Two important pending tasks in this respect are to set regulations that enhance cross border trade and foster competition so as to reduce the market concentration on the energy market in the European Union.

A very important ingredient of the aforementioned transnational market are the tariffs imposed on the gas transmission in the networks of the different members of the European Union. Designing these tariffs so that they do not have a detrimental effect on competition is a fundamental aspect towards a more efficient European natural gas industry.

In this direction, Regulation no. 715/2009 of the European Commission establishes that "Tariffs, or the methodologies used to calculate them, applied by the transmission system operators and approved by the regulatory authorities... shall be transparent, take into account the need for system integrity and its improvement and reflect the actual costs incurred, insofar as such costs correspond to those of an efficient and structurally comparable network operator and are transparent, whilst including an appropriate return on investments, and, where appropriate, taking account of the benchmarking of tariffs by the regulatory authorities. Tariffs, or the methodologies used to calculate them, shall be applied in a non-discriminatory manner."

The above regulation sets ambitious goals and achieving them requires a

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careful design of the underlying methodologies. The first part of a methodology deals with the calculation of the total revenue that the transmission system operators, hereafter TSOs, want to collect with the tariffs. A second part is concerned with the determination of the split of the revenue to collect between capacity and commodity charges and between entry and exit points. Then, a third part deals with the specifics of the computation of the tariffs. We mainly focus on this last part. Yet, we do not aim to cover all the different approaches, but to discuss in some detail one of them: entry-exit tariffs using the least squares methodology.[1] For an overview of the alternative approaches and discussions on their pros and cons, we refer the reader to Lapuerta and Moselle (2002), Hewicker and Kesting (2009), and ACER (2013). Also, the reader may refer to Cavaliere (2007) and Klop (2009) for two reports that assess the impact of the liberalization of the natural gas market and the new regulatory framework in individual EU members.

The reason to focus on the least squares methodology is that it seems that there is a wide consensus in the European Union towards the implementation of this approach. Some examples can be seen in Deliberata (2006), Alonso et al. (2010) and National Energy Comission of Spain (2012), and Apolinário et al. (2012), documents that discuss or regulate the use of least squares optimization in Italy, Spain, and Portugal, respectively.

In a context where many countries are revising their current tariffs it is our impression that, to some extent, regulatory authorities and TSOs are taking for granted that, once a methodology such as least squares has been agreed upon, the effort should be put in defining what costs should be collected with the tariffs. However, we consider that an important part of the derivation of these tariffs is being unattended: the final tariffs may vary a lot depending on how the specifics of the chosen methodology are tuned.

In this paper we want to raise awareness on the fact that the tariffs obtained via the least squares methodology are specially sensitive to the various ways in which it can be implemented. Maybe more importantly, for each of these methodological aspects we make a proposal that pretends to be aligned with the goals set forth by the European Commission.

With this objective in mind, we present the standard formulation of the derivation of the entry-exit tariffs via least squares in the next section. Then, we devote Section 3 to describe some implementation details that have to be handled carefully in order to meet the aforementioned goals set by the European Commission. For each of these details we present a proposal on how it can be dealt with. In Section 4 we illustrate some of our proposals in the context of the gas transport system in Spain.

2. Standard formulation of the least squares approach

The main goal of this paper is to discuss some technical aspects of the computation of entry-exit tariffs via the least squares approach. As we already said in the Introduction and as we illustrate in the upcoming sections, these technical aspects may have a huge impact on the resulting tariffs, so regulators and TSOs should be careful when deciding how to approach them.

In order to keep the focus of the paper, we abstract away from other important aspects of the entry-exit methodology, such as determining what costs should be recovered with the tariffs and how they should be assigned to the different infrastructures of the system. Thus, for the sake of exposition we take as a starting point a network in which a cost has been attributed to each of its pipelines. Given these costs, the least squares methodology builds upon the following elements:

- Total revenue to collect: R.
- A snapshot of the gas transport system, typically taken from a day of average/high/peak demand. We refer to this snapshot as the *reference scenario*. For this reference scenario we know the flows at all the pipelines in the network; they may come from historical flows or from simulation and optimization programs.
- In this reference scenario, the entry and exit points are clearly determined (with no point being into the two categories simultaneously). Let $F_i^{\text{ET}} > 0$ denote the amount of gas that enters the network through entry point i and, similarly, let $F_j^{\text{XT}} > 0$ denote the amount of gas that exits the network through exit point j.

- For each entry point i and each exit point j, we define C_{ij} as the cost of sending a unit of flow from i to j. To compute C_{ij}, the costs of the pipelines traversed in a direction opposite to the flow of gas in the reference scenario are multiplied by the so called *backhaul parameter*, which usually varies between 0 and 0.15. We discuss both the computation of the matrix C and the selection of the backhaul parameter in Section 3.2.

- Once the matrix C has been computed, it has as many rows as entry points and as many columns as exit points. Now we are ready to obtain, for each entry point, its tariff ET_i and, for each exit point, its exit tariff XT_j. Ideally, we would like to have tariffs such that, for each pair (i, j) of entry-exit points, $ET_i + XT_j - C_{ij} = 0$. However, in general this yields a system of equations with far more constraints than variables and we have to settle for tariffs that solve the following minimization problem:

$$\min \sum_{i,j} (ET_i + XT_j - C_{ij})^2, \tag{1}$$

  where this minimization has to be constrained so that all the resulting tariffs are nonnegative. Further, the resulting tariffs should be rescaled so that they collect revenue R.

In the following section we discuss several aspects that one should bear in mind when implementing the above methodology. Not only we discuss how to compute the C matrix and the backhaul parameter, but also other important procedural details such as how to avoid negative tariffs, how to rescale to collect total revenue, or how to control the split of the collected revenue between entry and exit points.

3. Technical observations regarding the general methodology

3.1. Collecting the total revenue R

Suppose that, after the application of Eq. (1), we have determined the vectors of tariffs, ET and XT. Recall that we use F_i^{ET} and F_j^{XT} to denote the flow through entry point i and exit point j, respectively. Then, the (expected) revenue to be collected with the entry-exit tariffs is

$$R^0 = \sum_{i \text{ entry}} F_i^{\text{ET}} \cdot ET_i + \sum_{j \text{ exit}} F_j^{\text{XT}} \cdot XT_j.$$

Since the entry and exit tariffs have been designed to minimize the terms $(ET_i + XT_j - C_{ij})^2$, there is no guarantee that $R^0 = R$. Therefore, one must rescale tariff via the factor $\gamma = \frac{R}{R^0}$ so that the total revenue R is collected. We denote the resulting tariffs by $ET_i^R = \gamma \cdot ET_i$ for each entry point i and by $XT_j^R = \gamma \cdot XT_j$ for each exit point j.

Since normalizations like the one we have just done may result in tariffs that do not solve anymore the minimization problem in Eq. (1), one must ensure that they are justified. In this case, since the normalization we have proposed applies equally to all tariffs, it is a harmless one. In particular, the new tariffs are a solution of the problem given by

$$\min \sum_{i,j} (ET_i^R + XT_j^R - C_{ij}^R)^2,$$

where, for each entry point i and each exit point j, $C_{ij}^R = \gamma \cdot C_{ij} = \frac{R}{R^0} \cdot C_{ij}$. Thus, the new tariffs are the solution of the least squares problem where the costs have been adequately rescaled to reflect the total revenue R and so the following proposal is fully justified.

Proposal 1. *Rescale all the tariffs multiplying them by the same scaling factor, so as to ensure that the total revenue R is collected.*

3.2. Obtaining the cost's matrix. Backhaul parameter

The C_{ij} element of matrix C should reflect the cost of sending one unit of flow from entry point i to exit point j. At the same time, when considering the cost of traversing a given pipeline, this cost should be adjusted with the backhaul parameter when it is traversed in the direction opposite to the flow of gas in the reference scenario. Recall that our starting point for the least squares approach is a network in which a cost $c_k > 0$ has been assigned to each pipeline k. Further, suppose that a backhaul parameter $\beta \in [0,1]$ has been selected. Based on the c_k costs and on β, we propose the following procedure to compute matrix C.

Proposal 2. *(i) Create a directed graph in which we have two edges for each pipeline of the network: one in the direction of gas flow with cost c_k and another one in the opposite direction with cost βc_k.*

(ii) For each entry point i and each exit point j, compute C_{ij} as the cost of the shortest path *between i and j in the graph we have just defined.*

The above procedure requires to compute as many shortest paths as the product of the number of entry points and the number of exit points. Fortunately, computing shortest paths in graphs with nonnegative costs is an easy problem and many efficient algorithms exist.[2]

Concerning the backhaul parameter, given that traversing pipelines in backhaul represents flows that would reduce congestion, it seems natural to consider $\beta = 0$. Along these lines, Harris and Wilson (2012) include a detailed discussion regarding capacity tariffs and suggest to use backhaul parameters as small as possible to favor flows that ease the congestion of the system.[3] In practice different values for the backhaul parameter have been considered, $\beta = 0.08$ is used in Italy (Deliberata, 2006) whereas Alonso et al. (2010) develop their analysis using $\beta = 0.15$.

3.3. Entry-exit split and uniqueness of the least squares solution

The formal derivation of the results described in this section can be found in Appendix A.

Once the cost matrix C has been obtained, the minimization problem in Eq. (1) is perfectly defined. For the discussion in this section we set aside the nonnegativity constraint, which we discuss in Section 3.4. Once this is done, it can be checked that the minimization problem has infinite solutions. More importantly, the infinite set of solutions can be completely characterized by a single parameter. Given optimal tariffs ET and XT and a constant $a \in \mathbb{R}$, the tariffs obtained adding a to all the entry tariffs and subtracting a from all the exit tariffs are also optimal.[4] Further, all of optimal tariffs can be obtained via the transformation of ET and XT through the appropriate k.

The above observation raises the natural question of how to select one solution out of infinitely many optimal ones. Fortunately, it can also be shown that, once the proportion of revenue to be collected through the entry points and the proportion to be collected through the exit points are fixed, there is a *unique solution* of the least squares problem that respects these proportions. This is summarized in the following proposal.

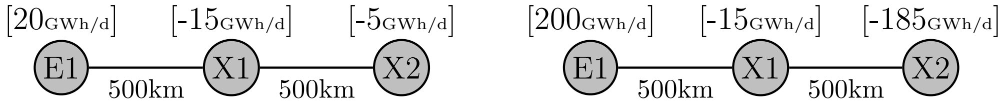
Proposal 3. *(i) Fix the proportion of revenue to be collected through entry points and the proportion to be collected through exit points.*

(ii) Select the unique optimal tariffs that deliver the desired split.

From the computational point of view, it can be shown that the infinite set of solutions can be obtained as the set of solutions of a system of linear equations, whose resolution nowadays is immediate in a desktop computer even if the number of entry and exit points is very large. To pin down the solution that satisfies the desired entry-exit split, one just needs to add the corresponding constraint to the system of linear equations.

In order to fix an appropriate split between entry and exit points, there is an aspect that may be taken into account, namely, the proportion of transit flows in the system. As we illustrate below, if transit flows are significantly higher than local demand, we may end up with tariffs in which most of the cost is borne by the cross-border points, a feature that may harm international flows and, in turn, the integration of the different national grids in a single market. However, as we discuss below, although the entry-exit split might mitigate these effects, additional measures might need to be taken to obtain tariffs at cross-border points that do not have detrimental effects on cross-border trade, in line with Article 13 in Regulation no. 715/2009.[5]

Consider the two scenarios depicted in Figure 1, and think of E1 and X2 as cross-border points and X1 as the local exit point. The first one corresponds to a situation in which local consumption is higher than transit flows and in the second one transit flows clearly dominate. In the tables we represent the tariffs resulting from the application of least squares with a



Tariffs (€/GWh)		
E1	X1	X2
68.49	41.10	150.69
Collected revenue (€)		
500000	225000	275000

Tariffs (€/GWh)		
E1	X1	X2
6.85	0.27	7.38
Collected revenue (€)		
500000	1478	498522

Figure 1: Entry-exit split and proportion of transit flows.

50-50 split between entry and exit points. We can see that, in the second example, the local exit point clearly benefits from the presence of transit flows. Importantly, since in the chosen networks we have one cross-border entry point and one cross-border exit point, no matter the chosen entry-exit split, X1 would have a low tariff in the high transit scenario, so additional measures might need to be taken concerning the tariffs at cross-border points.

3.4. Negative tariffs and tariff dispersion

When implementing the least squares methodology, there are two potential situations that regulator and TSOs would like to avoid:

- First, it must be ensured that no tariff is negative, since it is not admissible to pay shippers for using the network. To the best of our knowledge there is no reference in which a methodology to tackle negativities is proposed.
- Second, it would not be desirable to obtain tariffs with a big dispersion among them; at least not in the initial stages of a transition from postal tariffs to entry-exit ones, since dispersion might have a destabilizing effect in the system.

One possible option to control dispersion might just be to "compress" the tariffs in such a way that the same total revenue is collected, but tariffs are closer to each other. However, the problem of this approach is that the resulting tariffs would not be an optimal solution of the least squares problem anymore, so the compression approach goes against the very essence of the methodology under consideration. We now present a proposal that allows to tackle both negativity and dispersion at the same time in a natural way. The idea is to obtain the entry and exit tariffs as the sum of two components: one corresponding to postal tariffs and another one corresponding to entry-exit tariffs. Then, the regulator can choose how much of the total revenue is to be collected with the postal part (no dispersion, no negativity) and how much with the entry-exit one. Before formally stating our proposal, we illustrate it with an example.

3.4.1. Example of how to control negativity and dispersion

Suppose that we have a simple network with two entry points, E1 and E2, and two exit points, X1 and X2. The flow through each of these four points is 100 GWh/d. We want to collect the same revenue through entry and exit points. As we said above, this split automatically pins down a unique solution of the least squares problem. Suppose that the costs in the network are such that this solution is the one in Table 1.

	E1	E2	X1	X2
Tariffs	−50 €/GWh	800 €/GWh	375 €/GWh	375 €/GWh

Table 1: Initial tariffs.

With these numbers in mind we can easily calculate the revenue to be collected at each point. For instance, for the exit point X1 we get 375 euro per GWh. Thus, in one day we would collect $375\,€/\text{GWh} \cdot 100\,\text{GWh/d} = 37500\,€/\text{d}$. Multiplying this amount by 365 we would have the revenue in one year. Finally, the total revenue to collect in one year would be:

$$R = -50\cdot 100\cdot 365+800\cdot 100\cdot 365+375\cdot 100\cdot 365+375\cdot 100\cdot 365 = 54750000\,€/\text{year}.$$

We can see that point E1 has a negative tariff and, moreover, the tariff dispersion is quite big: 850 €/GWh. To control this, suppose that we decide that 20% of the money is to be collected with a postal tariff (uniform) and the remaining 80% via entry-exit with least squares; that is, $0.2 \cdot R$ will be collected with the postal tariff and $0.8 \cdot R$ with entry-exit. The postal part of the four tariffs would be $\frac{0.2 \cdot R}{100 \cdot 365 \cdot 4} = 75$ €/GWh. Adding this to the (rescaled) entry-exit tariffs we would get the new tariffs:

E1: $75 + 0.8 \cdot (-50) = 35$ €/GWh.

E2: $75 + 0.8 \cdot 800 = 715$ €/GWh.

X1: $75 + 0.8 \cdot 375 = 375$ €/GWh.

X2: $75 + 0.8 \cdot 375 = 375$ €/GWh.

These new tariffs are all positive and, further, the tariff dispersion has gone down exactly by 20%, from 850 to 680. Clearly, the total revenue collected is the same:

$$35 \cdot 100 \cdot 365 + 715 \cdot 100 \cdot 365 + 375 \cdot 100 \cdot 365 + 375 \cdot 100 \cdot 365 = 54750000 \text{ €/year}.$$

3.4.2. Formal proposal to control negativity and dispersion.

We present now a procedure that formalizes the above example and also takes into account the aspects considered in the other proposals.

Proposal 4. *(i) First of all, determine the total revenue to collect, R.*

(ii) Fix the proportion of revenue that will be collected through entry points, α, and the proportion to collect through exit points, $1 - \alpha$.

(iii) Fix the proportion of revenue that will be collected through postal tariffs, λ, and the proportion to collect through least squares tariffs, $1 - \lambda$.[6]

(iv) Compute the tariffs as follows:

(a) Calculate the postal tariffs for the entry points to collect $\lambda \cdot \alpha \cdot R$.

(b) Calculate the postal tariffs for the exit points to collect $\lambda \cdot (1 - \alpha) \cdot R$. So defined, the total revenue collected with postal tariffs is

$$\lambda \cdot \alpha \cdot R + \lambda \cdot (1 - \alpha) \cdot R = \lambda \cdot R.$$

Importantly, all the post tariffs are positive.

(c) Compute the least squares tariffs as the unique solution of Eq. (1) such that the split between entry and exit collected revenues is

given by α and $1 - \alpha$ (Proposal 3). These tariffs are rescaled as suggested in Proposal 1 so that the total revenue collected is $(1 - \lambda) \cdot R$.

(v) The final tariffs associated with each entry point and each exit point are obtained as the sum of its postal tariff and its least squares tariff.

Clearly, the more weight is assigned to the postal part (the closer λ is to one), the less dispersion we get in the final tariffs. Further, we can ensure that these tariffs are nonnegative by increasing λ as much as needed. Going back to the example in Section 3.4.1, the calculations there follow from the application of Proposal 4 with $\alpha = 0.5$ and $\lambda = 0.2$.

In order to determine an adequate value for the "homogenizing" parameter λ, one can take into account different factors such as security of supply, fostering competition, or tariff stability to mitigate forecast errors (see Section 3.4.2.2 on equalization in ACER 2013). In Appendix B we elaborate a bit more on the procedure to get a specific target for the dispersion between the lowest and the highest tariffs.

3.5. Network representation and weighted least squares

In order to apply the least squares methodology, it is essential to decide the level of precision with which to model the gas network. Yet, since all the necessary calculations are not demanding computationally, it seems natural to work with a network representation as fine as possible. This proposal is in contrast with the approach of using a fairly simplified representation at the province level (see, for instance, Alonso et al. (2010)). One of the problems of the simplified approaches is that they rely on an artificial network, less representative of the physical reality of the system.

Further, it is important to note that the level of detail chosen to represent the network may have important implications in the resulting tariffs. Recall that the philosophy of the least squares approach is to "penalize" a given entry point i for carrying flow to an exit point j that is far in the network (large cost C_{ij}). However, this penalization is independent of the total flow that enters/exits through these points. It seems natural to impose on the least squares problem a condition that ensures that, for point i, exit points with larger outgoing flows have more weight. We present below an example to illustrate that not doing so may result in unfair tariffs.

3.5.1. Example to illustrate the sensitivity of the tariffs to the network representation

Consider the network represented in the upper part of Figure 2. Clearly, since everything is symmetric, E1 and E2 will have the same entry tariff. Now, suppose that point X2 is split into two nodes: Y1 and Y2, each of them at the same distance from the rest of points as X2 and each of them with half the demand (half the outgoing flow). This second situation is depicted in the lower part of Figure 2. We claim that the tariffs of E1 and E2 should not be affected by the split of point X2 and yet, when recomputing matrix C, we find that from E1 we have to go twice as many times to distant exit points. Because of this, when solving the new least squares minimization problem, the tariff of E1 will now be significantly higher than the tariff of E2, which has to go twice as many times to nearby exit points.

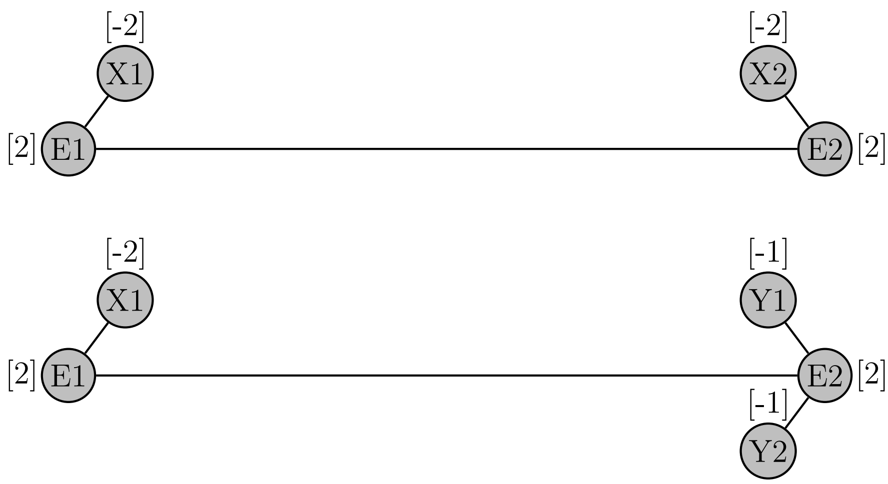


Figure 2: Importance of the network representation.

This problem can be easily addressed by considering a weighted least squares minimization, as we describe below.

Proposal 5. *If it is likely that a network representation suffers from problems as the one depicted in Figure 2, we suggest to replace the least squares problem in Eq. (1) with the following weighted version:*

$$\min \sum_{i,j} W_{ij} \cdot (ET_i + XT_j - C_{ij})^2, \tag{2}$$

where $W_{ij} = F_i^{\mathrm{ET}} \cdot F_j^{\mathrm{XT}}$*;* F_i^{ET} *and* F_j^{XT} *being the flows that enter and exit through the points* i *and* j*, respectively.*

Proposal 5 ensures that, even if a point splits into two (splitting also the associated flow), the tariffs of the rest of points in the network will be unaffected (this split point would now appear in twice as many addends in Eq. (2), but all of them with half the weight).

3.6. Selection of the benchmark scenario

The selection of the benchmark scenario may also have a big influence in the resulting tariffs. This choice determines the direction of the flows in the network and, therefore, it has a big impact on the computation of the C matrix, which depends crucially on the direction in which each pipeline is traversed (as long as the backhaul parameter is different from one). We divide our discussion regarding the benchmark scenario in two parts.

3.6.1. Selection of demands

In this respect, there seems to be a consensus in the literature to consider peak demand conditions in the transmission system (Apolinário et al., 2012; Alonso et al., 2010). Yet, recently, the ACER document (2013) recommends to use peak specifications (referred to as *technical capacity*) for expanding networks where locational signals are sought and use average conditions (*booked capacity*) otherwise. In order to mitigate the dependence of the final tariffs on the chosen demands we make the following proposal.

Proposal 6. *(i) Compute tariffs for different scenarios of demands (average/high/peak), representative of the physical reality of the network in the different seasons. Actually, since the computational requirements* *associated with this calculations are low, one might even consider the derivation of daily tariffs.*

(ii) The final tariffs for each entry and exit point are computed as the (possibly weighted) average of the tariffs obtained for the different representative scenarios.

3.6.2. Computing the flow distribution

Although in order to determine the direction of flows in a given scenario one can just look at the real network operation in the past, it seems more adequate to work with the optimal flow configuration for the given demands. In particular, this allows to work with forecast scenarios for which there is no data on past operation.

Proposal 7. *Consider a flow distribution that corresponds to an optimal operation of the network, in the sense that gas consumption at compression stations is minimized.*

3.6.3. Points with a dual entry-exit role

In many gas networks there are points that, depending on the demand in the chosen scenario, can act as entry or exit points. This may be the case, for instance, of underground storage facilities and international connections. This raises the question of what tariffs should be considered for these points. In this respect it is worth emphasizing that the methodology in Proposal 6 can be very useful. The entry tariff of one of these points would be the (weighted) average of the tariffs associated with this point in the scenarios where it is an entry point. Similarly, its exit tariff would be computed using the scenarios where it acts as an exit point.

4. Application to the Spanish gas network

In this section we apply the methodology discussed in the previous section to the Spanish gas transport network. For the illustration we use a scenario with the average demands in 2012, with the flows given by the optimal network configuration under the infrastructures that are projected to be operating by the end of 2013.[7]

In our analysis we take into account all the information available to us relative to the infrastructures of the gas network system. For the results we report, we consider the expected costs that the TSO would incur associated to the different infrastructures if these were one year old (this is to ensure that areas with new infrastructures are not penalized). Our analysis includes pipelines, compressor stations, valves, and regulation and measurement points. Since the compressors consume some fraction of the gas flowing through the pipelines, we also consider the associated cost (under the optimal flow configuration of the benchmark scenario). For our benchmark scenario, the total revenue to collect in the given year is $R = 1\,229\,317\,639$ €.[8]

As we mentioned in the previous section, since the methodology under study is not very demanding computationally, we can work with a very detailed representation of the Spanish transport network through a graph with more than 450 nodes and 550 edges.

Table 2 contains the resulting tariffs for the main entry points and some representative exit points of the Spanish network when applying the least squares and weighted least squares approaches.[9] The entry points correspond to regasification plants, international connections, and underground storage facilities. We also present the tariffs when Proposal 4 is applied to control for negative tariffs and tariff dispersion on entry points. Actually, it is worth noting that the results without controlling correspond to Proposal 4 with $\lambda = 0$. The parameters that we have used are:

- The same proportion of revenue to be collected through entry points and exit points, $\alpha = 0.5$.
- We consider backhaul $\beta = 0.08$.
- To control the dispersion we have required that the minimum entry tariff is, at least, 20% of the largest one. This specification immediately pins down the proportion λ of revenue to be collected through postal tariffs (see Appendix B for details).

In Figure 3 we represent the Spanish gas network and the tariffs corresponding to the (unweighted) least squares approach controlling for negativity and dispersion (second column in Table 2).

Entry points	Least squares		Weighted least squares	
	No control ($\lambda = 0$)	Control ($\lambda \approx 0.47$)	No control ($\lambda = 0$)	Control ($\lambda \approx 0.42$)
Almería (IC)	3166.24	2389.44	3110.16	2440.17
Barcelona (LNG)	1142.41	1325.60	864.01	1145.55
Bilbao (LNG)	−470.26	477.89	−275.08	489.00
Cartagena (LNG)	2238.35	1901.68	2152.84	1888.40
Gaviota (US)	−376.51	527.17	−183.45	541.82
Huelva (LNG)	588.92	1034.65	678.82	1038.81
Irún (IC)	−240.04	598.90	−54.83	615.95
Larrau (IC)	866.00	1180.30	940.02	1189.36
Marismas (US)	566.84	1023.05	664.53	1030.57
Mugardos (LNG)	257.99	860.70	534.88	955.84
Poseidón (GF)	604.05	1042.60	697.11	1049.35
Sagunto (LNG)	940.93	1219.69	756.23	1083.43
Serrablo (US)	209.52	835.22	150.10	734.07
Tarifa (IC)	2996.34	2300.13	3118.56	2445.02
(Sample) **Exit Points**				
X1	1826.25	1685.06	2063.89	1837.13
X2	1967.30	1759.21	2186.18	1907.61
X3	1627.89	1580.79	1809.87	1690.72
X4	1771.93	1656.51	1940.37	1765.93
X5	1384.48	1452.85	1469.31	1494.43
X6	1525.25	1526.84	1551.77	1541.95
X7	1465.80	1495.59	1482.82	1502.21
X8	1031.27	1267.18	972.76	1208.23
X9	1008.39	1255.15	835.81	1129.3
X10	1797.54	1669.97	2029.87	1817.52

Table 2: Least squares methodology. Tariffs in €/GWh.
(LNG=regasification plant, IC=international connection, US=underground storage, GF=gas field)

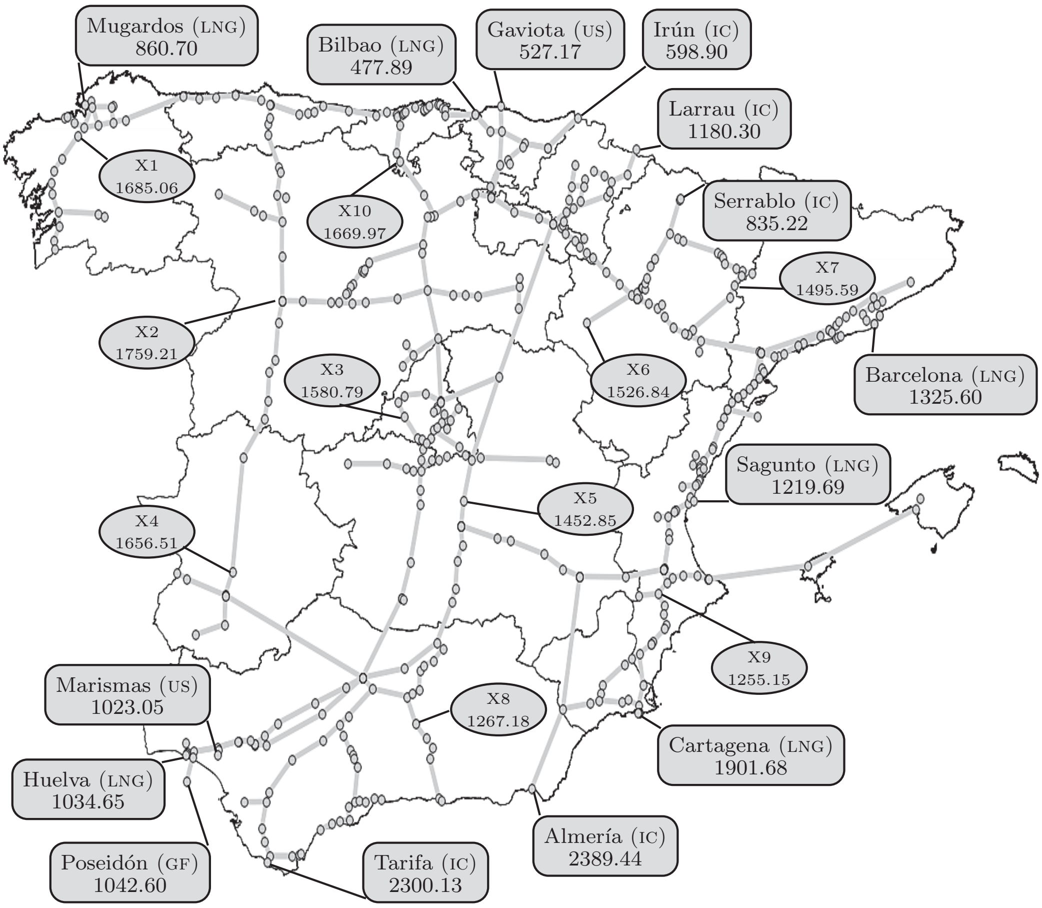


Figure 3: Spanish gas transport network with entry tariffs computed following Proposal 4.

We can see in Table 2 that the tariffs applying least squares with and without weights are quite similar, so the concerns raised in Section 3.5 regarding the network representation do not seem to be too critical for the fine modeling we have chosen for the Spanish network. It is important to note that, without control for negative tariffs and dispersion, there are some negative tariffs and the dispersion exceeds 3600 €/GWh. On the other hand, when Proposal 4 is applied to control for these effects, all resulting tariffs are positive and dispersion is roughly 50% of the original one (around 1900 €/GWh). This comes from the fact that, to accomplish this reduction, 47% of the final tariffs came from the (flat) "postal component" and 53% from the entry-exit one. It is also worth noting that in this example dispersion turns out to be much more accused in entry points than in exit points, which suggests that it would be interesting to explore whether or not this is a specific aspect of the Spanish network or the chosen configuration.

Finally, we would like to note that the computational effort required to undergo all the computations above, including the optimal flow configuration, was under three minutes in a standard desktop computer. The computer programs were implemented in Fortran 2003 and make use of standard open source libraries.

5. Conclusions

The driving force of this paper is the observation that, regardless of the chosen methodology for the computation of the tariffs to be charged for the use of the national gas transmission networks, the implementation of a given methodology typically leaves some freedom to the modeler that might significantly influence the results.

We have focused on a specific methodology, entry-exit tariffs via least squares, that seems to be widely accepted at least within the members of the European Union. Below we briefly recall some of the implementation issues we have discussed.

An important observation deals with the sensitivity of the resulting tariffs with respect to the network representation. We have presented an example illustrating how apparently equivalent networks may lead to different tariffs. To account for this, we have presented a weighted version of the least squares methodology (Proposal 5).

Another important concern of the regulatory bodies and TSOs when changing the tariff system is related to the big impact this might have on the underlying market. In this respect we have presented, in Proposal 4, an alternative that allows to control for the tariff dispersion, providing a tool to facilitate smoother transitions between tariff systems.

When making secondary adjustments on the tariffs one has to be careful to make them in such a way that they are consistent with the philosophy of the chosen methodology. Along these lines, Proposal 1 shows how to rescale the tariffs obtained by solving the least squares optimization problem so that they preserve the spirit of this minimization.

Overall, we have argued that, if tariffs are to be designed so that they meet the goals set by the European Comission (Regulation no. 715/2009), both regulators and TSOs should be aware of the potential consequences of the different specifications available for the given methodology. It is only through the awareness of these and other modeling aspects that we can expect to move in the right direction towards more efficient national and European natural gas industries.

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Notes

[1]In a recent document by ACER (Agency for the cooperation of energy regulators, 2013), this methodology is referred to as *matrix methodology*.

[2]One could rely, for instance, on Dijkstra's algorithm or Floyd-Wharshall's algorithm; for a detailed coverage of the shortest path problem and algorithms to solve it the reader may refer, for instance, to Bazaraa et al. (2010) or Ahuja et al. (1993).

[3]Indeed, going one step further, it might even be worth studying the consequences of a negative backhaul parameter (*e.g.*, $\beta = -1$). This is the approach taken in the United

Kingdom within the Long Run Marginal Cost methodology. Refer, for instance, to the report of the National Grid (2011).

[4]This can be readily checked by noting that they deliver the same value in all addends in the sum in Eq. (1).

[5]These additional measures would be part of what is referred to as *benchmarking* in ACER (2013), Section 3.4.2.3.

[6]The proportion λ can be determined, for instance, to deliver a desired level of dispersion in terms of the quotient between the smallest and largest tariffs. In Section 4 we present an analysis in which the minimum tariff is required to be, at least, 20% of the largest tariff.

[7]For those points with a dual entry-exit role we impose an entry flow equal to their average flow in the periods in which they act as entry points.

[8]In the case in which there is no so much information about the infrastructures of a transport network, one can just work on the basis that costs are proportional to the length or surface of the pipelines.

[9]For the sake of exposition, since there are more than 300 exit points in the network, we have chosen not to present the corresponding tariffs.

Appendix A. Mathematical analysis of the least squares method

Consider a gas transport network with n entry points and m exit points. We have a matrix C such that C_{ij} represents the cost of sending a unit of flow from entry point i to exit point j, where $1 \leq i \leq n$ and $1 \leq j \leq m$.

Ideally, we would like to break down this cost matrix and get a unitary cost for each entry, $ET_i, i \in \{1, \ldots, n\}$, and another one for each exit $XT_j, j \in \{1, \ldots, m\}$, so that

$$ET_i + XT_j = C_{ij}\,, \quad 1 \leq i \leq n,\ 1 \leq j \leq m. \tag{A.1}$$

However, the number of unknowns, $n + m$, is generally much lower than the number of equations, $n \times m$, so the system (A.1) will be incompatible. Therefore, under the least squares methodology the problem is reformulated as follows. Suppose we are given a matrix W of weights, where $W_{ij} > 0$ represents the weight corresponding with the pair formed by entry point i and exit point j.[10] We want vectors $\mathbf{ET} \in \mathbb{R}^n$ and $\mathbf{XT} \in \mathbb{R}^m$ that minimize the function:

$$\frac{1}{2} \cdot \sum_{i=1}^{n} \sum_{j=1}^{m} W_{ij} \cdot (ET_i + XT_j - C_{ij})^2 .$$

Unless we say otherwise, we will work with column vectors. Given a matrix A, $A_{\cdot j}$ denotes the jth column of A. In order to write this problem in a compact way, we introduce the following notation:

$$\mathbf{X} = \begin{pmatrix} \mathbf{ET} \\ \mathbf{XT} \end{pmatrix}, \quad \mathbf{b} = \begin{pmatrix} C_{\cdot 1} \\ C_{\cdot 2} \\ \vdots \\ C_{\cdot m} \end{pmatrix}, \quad \text{and} \quad \mathbf{p} = \begin{pmatrix} W_{\cdot 1} \\ W_{\cdot 2} \\ \vdots \\ W_{\cdot m} \end{pmatrix}.$$

Note, in particular, that $C_{ij} = b_{(i-1)m+j}$. Let

$$\mathcal{A} = \begin{pmatrix} \mathbf{e^m} & \mathbf{0} & \dots & \mathbf{0} & \mathbf{I}_m \\ \mathbf{0} & \mathbf{e^m} & \dots & \mathbf{0} & \mathbf{I}_m \\ \vdots & \vdots & \ddots & \vdots & \vdots \\ \mathbf{0} & \mathbf{0} & \dots & \mathbf{e^m} & \mathbf{I}_m \end{pmatrix}, \quad \mathcal{A} \in \mathcal{M}_{(n\times m)\times(n+m)}$$

where

$$\mathbf{e^m} = \begin{pmatrix} 1 \\ \vdots \\ 1 \end{pmatrix} \in \mathbb{R}^m, \quad \mathbf{0} \in \mathbb{R}^m, \quad \text{and} \quad \mathbf{I}_m = \begin{pmatrix} 1 & 0 & \dots & 0 \\ 0 & 1 & \dots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \dots & 1 \end{pmatrix} \in \mathbb{R}^{m\times m}.$$

With these notations we obtain

$$\frac{1}{2} \cdot \sum_{i=1}^{n} \sum_{j=1}^{m} W_{ij} \cdot (ET_i + XT_j - C_{ij})^2 = \frac{1}{2} \cdot \|\mathcal{A}\mathbf{X} - \mathbf{b}\|_{\mathbf{p}}^2 ,$$

where $\|\mathbf{Y}\|_{\mathbf{p}}^2 := (\mathbf{Y}, \mathbf{Y})$ and $(\mathbf{Y}, \mathbf{Z}) := \sum_{k=1}^{n\times m} p_k \cdot y_k \cdot z_m$.

From the first order conditions of the optimization problem

$$\min_{\mathbf{X}\in\mathbb{R}^{n+m}} \frac{1}{2} \cdot \|\mathcal{A}\mathbf{X} - \mathbf{b}\|_{\mathbf{p}}^2$$

we get $(\mathcal{A}\mathbf{X}-\mathbf{b},\mathcal{A}\mathbf{Y})_{\mathbf{p}}=0, \quad \forall\,\mathbf{Y}\in\mathbb{R}^{n+m}$. Now, if we consider the matrix $\mathcal{P}=\text{diag}\,(\mathbf{p})\in\mathcal{M}_{(n\times m)\times(n\times m)}$, the previous equation is equivalent to[11]

$$\mathcal{A}^t\mathcal{P}\mathcal{A}\mathbf{X}=\mathcal{A}^t\mathcal{P}\mathbf{b}. \tag{A.2}$$

Let $\mathcal{D}=\mathcal{P}^{\frac{1}{2}}\mathcal{A}$ and $\mathbf{u}=\mathcal{P}^{\frac{1}{2}}\mathbf{b}$. Then, Equation (A.2) can be rewritten as

$$\mathcal{D}^t\mathcal{D}\mathbf{X}=\mathcal{D}^t\mathbf{u}\,. \tag{A.3}$$

We now prove that $\text{Ker}\,(\mathcal{D}^t\mathcal{D})=\text{Ker}\,(\mathcal{D})=\text{Ker}\,(\mathcal{A})$. In fact, if $\mathbf{Y}\in\text{Ker}\,(\mathcal{D}^t\mathcal{D})$, then

$$\mathcal{D}^t\mathcal{D}\mathbf{Y}=0\Rightarrow\mathbf{Y}^t\mathcal{D}^t\mathcal{D}\mathbf{Y}=0\Rightarrow(\mathcal{D}\mathbf{Y})^t\mathcal{D}\mathbf{Y}=0\Rightarrow\|\mathcal{D}\mathbf{Y}\|^2=0\Rightarrow\mathcal{D}\mathbf{Y}=0.$$

Thus, $\mathbf{Y}\in\text{Ker}\,(\mathcal{D})$. In addition, since $\mathcal{P}^{\frac{1}{2}}$ is invertible, then $\mathcal{A}\mathbf{Y}=0$ and so $\mathbf{Y}\in\text{Ker}\,(\mathcal{A})$. The reciprocals are straightforward.

Let $\mathbf{Y}\in\mathbb{R}^{n+m}$ be the vector

$$\mathbf{Y}=\begin{pmatrix}\mathbf{e^n}\\-\mathbf{e^m}\end{pmatrix}.$$

It is easy to see that $\mathbf{Y}\in\text{Ker}\mathcal{A}=\text{Ker}\,(\mathcal{D}^t\mathcal{D})$. Moreover, if we remove the first column from $\mathcal{A}$, the remaining ones are linearly independent. Therefore, $\text{rank}\,(\mathcal{A})=n+m-1$ and $\dim\,(\text{Ker}\,(\mathcal{A}))=1$, which implies that

$$\text{Ker}\left(\mathcal{D}^t\mathcal{D}\right)=\text{Ker}\mathcal{A}=\langle\mathbf{Y}\rangle\,.$$

Thus, the system (A.3) has solution if and only if $\mathcal{D}^t\mathbf{u}\in\text{Im}\,(\mathcal{D}^t\mathcal{D})$. Since $\mathcal{D}^t\mathcal{D}$ is a symmetric matrix, the image set is precisely the subspace of $\mathbb{R}^{n+m}$ orthogonal to the kernel $\text{Im}\,(\mathcal{D}^t\mathcal{D})=\langle\mathbf{Y}\rangle^{\perp}$. Therefore, since

$$(\mathcal{D}^t\mathbf{u})^t\mathbf{Y}=\mathbf{u}^t\mathcal{D}\mathbf{Y}=\mathbf{u}^t\mathbf{0}=0,$$

we have that $\mathcal{D}^t\mathbf{u}\in\text{Im}\,(\mathcal{D}^t\mathcal{D})$.

Given a solution $\mathbf{X}$ of system (A.3), the set of all the solutions is given by $\{\mathbf{X} + s\mathbf{Y},\ s \in \mathbb{R}\}$. In order to pin down exactly one of them, we can look for the solution $\bar{\mathbf{X}}$ such that

$$\mathbf{Z}^t \bar{\mathbf{X}} = \mathbf{Z}^t \left(\mathbf{X} + s \cdot \mathbf{Y} \right) = \beta \,,$$

being $\mathbf{Z}$ an arbitrary vector non-orthogonal to $\mathbf{Y}$. This yields $\mathbf{Z}^t\mathbf{X} + s \cdot \mathbf{Z}^t\mathbf{Y} = \beta$ and, consequently, since $\mathbf{Z}^t\mathbf{Y} \neq 0$,

$$s = \frac{\beta - \mathbf{Z}^t\mathbf{X}}{\mathbf{Z}^t\mathbf{Y}}, \quad \text{and we get} \quad \bar{\mathbf{X}} = \mathbf{X} + \frac{\beta - \mathbf{Z}^t\mathbf{X}}{\mathbf{Z}^t\mathbf{Y}}\mathbf{Y}.$$

The procedure to pin down a unique solution may be seen more transparently by looking directly at the linear system. We are imposing the condition $\mathbf{Z}^t\mathbf{X} = \beta$ as a restriction on top of the first order conditions given by

$$\mathcal{D}^t\mathcal{D}\mathbf{X} = \mathcal{D}^t\mathbf{u}.$$

The key is that the resulting linear system,

$$\begin{pmatrix} \mathcal{D}^t\mathcal{D} & \mathbf{Z} \\ \mathbf{Z}^t & \mathbf{0} \end{pmatrix} \begin{pmatrix} \mathbf{X} \\ \mathbf{0} \end{pmatrix} = \begin{pmatrix} \mathcal{D}\mathbf{u} \\ \beta \end{pmatrix}, \tag{A.4}$$

has non-singular matrix (we omit the proof, since the result is already implied by the above arguments).

Going back to the fact that $\mathbf{X}$ is composed of the entry and exit tariffs, $\mathbf{ET}$ and $\mathbf{XT}$, it is important to interpret the restrictions of the form $\mathbf{Z}^t\mathbf{X} = \beta$ in the setting under study. Interestingly, what they mean is that, for any split of the total revenue to be collected between entry and exit points, there is a unique solution delivering that exact split. For instance, if we want to ensure that half of the total revenue is collected with entry points and the other half with exit points, we would have

$$\sum_{i=1}^{n} F_i^{\text{ET}} \cdot ET_i = \sum_{j=1}^{m} F_j^{\text{XT}} \cdot XT_j,$$

where F_i^{ET} and F_j^{XT} denote the (nonnegative) flow through entry point i and exit point j, respectively. In this case,

$$\mathbf{Z} = \begin{pmatrix} \mathbf{F}^{\text{ET}} \\ -\mathbf{F}^{\text{XT}} \end{pmatrix}$$

and the condition $\mathbf{Z^t Y} \neq 0$ reduces to $\sum_{i=1}^{n} F_i^{\text{ET}} + \sum_{j=1}^{m} F_j^{\text{XT}} \neq 0$, which is satisfied for any non-trivial flow configuration.

Appendix B. Targeting a specific dispersion

In Section 3.4 we discussed two potential problems of the standard least squares methodology: the tariffs may be negative and we can obtain tariffs with a large dispersion among then. In Proposal 4 we have shown a procedure to conveniently handle these problems. The key ingredient in this approach is parameter λ, the proportion of revenue to be collected through postal tariffs. Next we show how to choose λ to avoid negative tariffs and target a certain dispersion level.

Given a vector ET entry tariffs we want to control the dispersion among them by controlling the value K defined as

$$K = \frac{\min(\mathbf{ET})}{\max(\mathbf{ET})}.$$

For instance, if $K = 0.2$, we have that the lowest entry tariff is 20% of the highest one. Thereby, the closer K is to 1 the smaller the dispersion we get.

Now, suppose that we have obtained the vectors of entry and exit tariffs, ET and XT, applying Proposal 4 with $\lambda = 0$. For these tariffs define $D = \max(ET) - \min(ET)$, the maximum difference between entry tariffs. Now, if we apply Proposal 4 with a certain parameter λ to obtain new vectors of tariffs $\hat{ET}$ and $\hat{XT}$, it is easy to check that we have

$$\hat{ET} = \lambda \cdot M + (1 - \lambda) \cdot ET,$$

where $M = \frac{R \cdot \alpha}{\sum_{i \text{ entry}} F_i^{\text{ET}} \cdot 365}$, and so $\max(\hat{ET}) - \min(\hat{ET}) = (1 - \lambda) \cdot D$.

Controlling negativity: If we want to ensure nonnegative tariffs we have to take λ to be at least as large as the solution of the equation:

$$0 = \min(\hat{ET}) = \lambda \cdot M + (1-\lambda) \cdot \min(ET) \Leftrightarrow \lambda = \frac{\min(ET)}{\min(ET) - M}.$$

Controlling dispersion: Suppose that we want to control dispersion by ensuring that $\frac{\min(\hat{ET})}{\max(\hat{ET})}$ reaches at least a given threshold $\hat{K}$. Now, if we take

$$1 - \hat{K} = \frac{\max(\hat{ET}) - \min(\hat{ET})}{\max(\hat{ET})} = \frac{(1-\lambda) \cdot D}{\lambda \cdot M + (1-\lambda) \cdot \max(ET)}$$

and solve for λ we get

$$\lambda = \frac{D - (1-\hat{K}) \cdot \max(ET)}{(1-\hat{K}) \cdot (M - \max(ET)) + D}.$$

Thus, to ensure that the threshold given by $\hat{K}$ is achieved it suffices to take λ as least as large as the above value.

A similar analysis could have been carried out to control for the dispersion among exit tariffs or entry and exit tariffs together.