OLIVEIRA, F.S., RUIZ, C. and CONEJO, A.J. 2013. Contract design and supply chain coordination in the electricity industry. *European journal of operational research* [online], 227(3), pages 527-537. Available from: https://doi.org/10.1016/j.ejor.2013.01.003

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2013

Published: *European Journal of Operational Research*,

http://dx.doi.org/10.1016/j.ejor.2013.01.003, 2013

Contract Design and Supply Chain Coordination in the Electricity Industry

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Abstract

In this article we propose a model of the supply chain in electricity markets with multiple generators and retailers and considering several market structures. We analyze how market design interacts with the different types of contract and market structure to affect the coordination between the different firms and the performance of the supply chain as a whole. We compare the implications on supply chain coordination and on the players' profitability of two different market structures: a pool based market vs. bilateral contracts, taking into consideration the relationship between futures and spot markets. Furthermore, we analyze the use of contracts for differences and two-part-tariffs as tools for supply chain coordination. We have concluded that there are multiple equilibria in the supply chain contracts and structure and that the two-part tariff is the best contract to reduce double marginalization and increase efficiency in the management of the supply chain.

Keywords: Contract design, game theory, OR in energy, supply chain management.

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1. Introduction

Electricity trading, in liberalized markets such the Iberian Peninsula, OMIE (2012), occurs through different trading channels (forward contracts, futures markets, day-ahead markets) and via different types of contract such as two-part-tariffs and contracts for differences. Our article aims at modeling the electricity supply chain taking into account the interaction between market structure and contracting (as in Borenstein et al., 1995; Sweetser, 1998; Joskow and Khan, 2002, for example). Within this framework, our model considers multiple generators with oligopoly power and multiple retailers with oligopsony power as well, as is the case in most electricity markets, in both spot and futures markets, and compares the implications of two different market structures, the pool based market vs. a bilateral trading based market, and of two different types of bilateral contracts, the contract for differences and the two-part tariffs.

The model proposed in this article is close to the analysis in Majumder and Srinivasan (2006, 2008) as we consider a network of supply chains and look at two part-tariffs to solve the double marginalization problem. Our main contributions are as follows. A) We model the supply chain network underlying a liberalized electricity market taking into consideration different types of contractual arrangements. B) We model bilateral contracts (forward contracts, contract for differences and the two-part tariffs contracts) and their interactions with a spot market where both retailers and generators trade electricity, just before the retailers sell to a price dependent demand. C) We propose a model of demand that considers that retailers have market power and in which each one of them has a different market share (even if the market price is the same). D) We derive the supply chain Nash equilibrium for the general structure considering the interaction between spot and futures markets in a network of supply chains. E) We derive the Nash equilibrium of the generalized supply chain considering the contract for differences and the two-part tariff. F) Finally, we apply our model to the analysis of a case study based on the Iberian electricity market.

The remaining of this paper is organized as follows. In Section 2 we provide an overview of the literature on supply chain management in electricity markets. In Section 3 we introduce a general supply chain model to represent the complexities of the interactions between generators and retailers. In Section 4 we derive the conditions for the supply chain Nash Equilibrium. In Section 5 we consider contracts for differences and the two-part tariff. In

Section 6 we present a case study based on the Spanish electricity market and in Section 7 we conclude the article.

2. Literature Review in the Electricity Markets Supply Chain

In this section we provide an overview of the very extensive literature on supply chain coordination, focusing, in particular, on the contractual arrangements that are important in electricity markets. We start in Section 2.1 by presenting a general overview of supply chain coordination and contract design; then, in Section 2.2 we analyze the different types of contracts used in electricity markets to improve the supply chain coordination; and finally, in Section 2.3 we conclude the literature review with an analysis of the problem of double marginalization, summarizing a series of articles that have used two-part tariffs to address this issue.

2.1 Supply Chain Coordination and Contract Design

The effectiveness of supply chain coordination affects the performance of each one of its members and of the supply chain as a whole. It is well known that the gains from supply chain coordination include better inventory management (Hult et al., 2002; Wisner and Tan, 2000), improved product and service quality and faster delivery (Handfield, 1994), and superior innovation (Morgan and Monczka, 1995; Tan, 2002; Biehl et al., 2006). In this sub-section we focus our summary on two specific topics on supply chain coordination: the exchange of information aimed at improving inventory management (mainly) in the supply chain; and the design of contracts for supply chain coordination.

Information sharing for supply chain coordination is a very well researched topic. Here, we summarize a set of relevant examples to illustrate the main issues analyzed in the literature. Xia, Chen and Kouvelis (2008) have analyzed the coordination in a supply chain with multiple buyers and suppliers arguing that the matching of the buyers' order profiles to the suppliers' cost structure is the main source of supply chain coordination in a many-to-many supply chain. Bernstein and Federgruen (2007) have shown that it is possible for a decentralized supply chain with independent retailers buying from the same supplier to be perfectly coordinated under price and service competition. Gullu et al. (2005) have analyzed a supply chain consisting of a supplier and two independent retailers proving that there is a unique Nash equilibrium for the retailer order-up-to levels. Watson and Zheng (2005) have shown that real-time sales data sharing can eliminate information delay, improving supply chain coordination. Balakrishnan et al. (2004), using a supply chain consisting of one supplier and several retailers as a base of study, have analyzed how supply chain coordination can be used to mitigate demand uncertainty; they have proposed a downstream inventory smoothing system to reduce order size variability. Kulp et al. (2004) have used a survey to test if a manufacturer benefits from information integration with a retail customer: they have concluded that collaborative planning on replenishment is correlated to an increase in manufacturer's margins; whereas collaboration on new product and service development tends to lead to higher wholesale prices and lower retailer and manufacturer stockouts.

The coordination of the activity in the supply chain can be enforced by contracts: "A contract is said to coordinate the supply chain if the set of supply chain optimal actions is a Nash equilibrium…", Cachon (2003, p. 230). The contract should be such that it Pareto dominates the non-coordinated Nash equilibrium, i.e., the firms are better off by signing the contract. Cachon (2003) explains how these two features can be very expensive to get in a contract and that, for this reason, a simpler contract that is not optimal but that closely approximates the optimal solution may be preferred instead. Zhang (2006), in analyzing the role of information sharing in supply chain coordination, has concluded that the Nash equilibrium exists but is not optimum; moreover; by using a transfer payment contract, it is shown that the perfect coordination is attained at the Nash equilibrium. Miyaoka and Hausman (2008) have studied the impact of demand uncertainty on supply chain coordination (considering one supplier and one manufacturer) under different assumptions for wholesale price formation, showing that information sharing increases the supply chain profit, and presenting a contract that provides flexibility in dividing the supply chain profit among its members. Krishnan et al. (2004) have discussed the possible negative effects of quick response and reduced retailer's inventory on the sales effort: they have suggested that the manufacturer should use minimum-take contracts, advanced-purchase discounts, and exclusive dealing as a way to correct the negative incentives created by quick response.

2.2 Contracts and Supply Chain Coordination in Electricity Markets

Historically, there have been two market structures used as base to the liberalization of electricity markets. The first type is the pool in which an auctioneer clears the market, every half-hour (typically), computing prices and trading quantities. The pool consists of a day-ahead market and a market for balancing demand and supply in real time. This was the case of the early stages of the market in England and Wales, and it is the case of major markets today, such as the Iberian and Australian markets, among many others, as described, e.g., by Anderson and Philpott (2002). Typically, in these markets electricity is mostly traded in the spot market. In order to hedge risk, the generators and retailers celebrate contracts for differences in which a sale price is agreed in advance: these contracts use the pool price as reference, e.g., Green and Newbery (1992).

The second type of electricity market is based on bilateral contracts which generators and retailers use to trade electricity. In this market structure spot and futures markets are important but not all the electricity is traded in the electricity auction, which is used only for some last adjustments to the players' trading positions, i.e., to adjust how much they contracted to buy and sell before electricity delivery (e.g., Bunn and Oliveira, 2001, 2003).

Therefore, one of the important determinants of the type of interaction between generators and retailers is the role played by spot markets (in which electricity is traded close to delivery time) and futures markets (in which electricity is traded months or days ahead of delivery), e.g., Allaz (1992), Allaz and Vila (1993), and Dong and Liu (2007). The importance of the relationship between futures and spot trading, in electricity markets, has previously been analyzed under different perspectives: Murphy and Smeers (2005) and Kazempour, Conejo and Ruiz (2012) have looked at the interaction between futures and spot markets in shaping investment decisions in oligopolies; Carrión et al. (2007) have analyzed the optimal trading strategy for a retailer, and Conejo et al. (2008) from the perspective of a producer, taking into consideration the relationship between futures and spot markets.

The implication of the presence of futures and spot markets on the firms' strategies and social welfare is an issue which is still the object of intense debate. Allaz (1992) and Allaz and Vila (1993) have argued that, given a concentrated generation market structure, the introduction of futures markets leads to lower spot equilibrium prices. Herguera (2000) and Le Coq and Orzen (2006) have analyzed, empirically, the implications of futures markets on market efficiency, finding evidence supporting this hypothesis. Bushnell (2007) has addressed the issue of the relationship between futures and spot markets and the implications for the generators pricing strategies and social welfare; and Anderson and Hu (2008), in the context of supply function equilibria, analyze market power issues when the retailers offer forward contracts to generators. All of these articles support the idea that the presence of futures markets, in the context of oligopolistic industries, lead to lower prices and increased social welfare. Gulpinar and Oliveira (2012) have looked at the relationship between future and spot markets taking into account the degree of risk aversion of generators: they concluded that, when the generators are homogeneous, risk-averse generators trade more in the futures market and produce more than risk neutral generators.

However, the impact that futures or contract markets have on spot prices is still controversial. Mahenc and Salanie (2004) showed that, in a Bertrand duopoly, firms buy their own production in the futures markets, increasing equilibrium prices. An important type of contract, in the case of electricity pool markets, is the contract for differences, which allows firms to manage the uncertainty associated to spot prices. A contract for differences is a financial derivative (it does not involve physical delivery) that can be used by both generators and retailers to protect themselves from the price and energy fluctuations that typically arise in the spot electricity market. Using this contract generators and retailers decide to fix a strike price for a particular time horizon so that, at the end of it, if the spot price at that time is higher than the strike price agreed, the generator pays the difference to the retailer. On the contrary, if the strike price is higher than the actual spot price, the retailer pays the difference to the generator. It is well known (e.g., Green and Newbery, 1992; Anderson and Philpott, 2002; Hortaçsu and Puller, 2008) that these contracts tend to lower the pool price.

2.3 Double Marginalization and the Two-Part Tariff Contract

The discussion on double marginalization can be traced back to the analysis by Spengler (1950) on successive monopolies and by Greenhut and Ohta (1979) on successive oligopolies. The double marginalization problem arises when an upstream firm (that has market power) sells to a downstream firm at a price above marginal cost. If the downstream firm also has market power it will choose to sell at a higher price and at a lower volume than the ones that would maximize joint profits (e.g., Neuman et al., 2005; Lafontaine and Slade, 2008).

Double marginalization has been analyzed in supply chains in the context of the design of coordination mechanisms (e.g., Netessine and Zhang, 2005; Chen et al., 2006; Heese, 2007). Netessine and Zhang (2005), in analyzing a supply chain with a wholesale producer and multiple retailers facing stochastic demand, have identified two sources of inefficiencies: double marginalization and externalities among retailers (i.e., the stockpiling decisions of one retailer affects the profits of the other retailers.) They have concluded that supply chain coordination is more important when there is competition among retailers in the presence of positive externalities. Chen et al. (2006) have proposed a risk sharing contact for a supply chain with a manufacturer and a retailer in which the retailer may partially compensate the manufacturer in case of over-production and the manufacturer compensates the retailer in case of overstocking: this contract is able to eliminate double marginalization. Heese (2007) has analyzed the relationship between inventory control inaccuracy and the double marginalization issue in a supply chain (with a Stackelberg manufacturer that sets the wholesale price and a retailer that determines how much stock to sell) concluding that inventory inaccuracies exacerbate this issue. He has also analyzed the conditions under which the presence of double marginalization makes it more difficult for the supply chain to adopt automated inventory control.

The most commonly tool used to solve the double marginalization problem is the two-part tariff contract by which the retailer pays the producer a fixed access fee for the right to buy its production and a per-unit price for each unit of production the retailer purchases. However, in the oligopoly case the solution of the double marginalization problem is complex and it is industry dependent, see e.g., Rey and Vergé (2005).

We proceed by reviewing a number of examples in which double marginalization in supply chains was solved using two-part tariffs. Majumder and Srinivasan (2006) have analyzed the effect of contract leadership (i.e., the ability to offer the wholesale price and the two-part tariff) on supply chain performance. They have considered a sequential supply chain in which a manufacturer (with increasing marginal costs) supplies a retailer that sells to a final consumer. Their main contribution was to extend the concept of double marginalization to the sequential supply chain with increasing marginal costs at the manufacturing level. They have shown that double marginalization also occurs when the downstream member is the one offering the contract to the upstream member. Moreover, they have reported that there is a first mover advantage in wholesale price contracting which is stronger when using two-part tariffs. Majumder and Srinivasan (2008) extended this idea of double marginalization of the cost function to a network of supply chains, considering price dependent demand. They have shown that contract leadership, and the position of the leader in the network, affect the performance of the supply chain. Lau et al. (2008) have also analyzed the use of two-part tariffs for supply chain coordination in the presence of a leader (retailer). They have reported that, in this case, the two-part tariff contract performs well and is a viable alternative to the more complex menu of contracts scheme in increasing the retailer’s profit. Schlereth et al. (2010) provided a mixed-integer nonlinear programming optimization problem to determine profit-maximizing two-part tariffs. They stated that a requirement to offer a pay-per-use tariff in addition to two-part tariffs lowers profitability, as consumers tend to have lower usage, because they are content with small volumes, reducing profitability. Ferrer et al. (2010) have analyzed how two-part tariffs (by considering a subscription fee) for pricing bundles of services and products, with the objective of avoiding switching between bundles of products, leads to an increase of the customer base per bundle, and to increased profitability. Aydin and Hausman (2009) have studied the issue of slotting fees (i.e., the manufacturer pays the retailer a per-product fee for every product the retailer accepts to hold in excess of a given minimum order) in coordinating assortment decisions in a single-retailer and single-manufacturer supply chain, proving that this payment scheme, which in essence is a two-part tariff, induces the retailer to offer the optimal assortment of products for the supply chain, increasing the profits of both players. Lantz (2009) has analyzed the double marginalization problem in a bilateral monopoly reporting that the optimal solution was found (with no double marginalization), without central planning, by using a two-part tariff. He has tested the model results in laboratory experiments with business students concluding that the pricing mechanisms are more important than direct negotiations in obtaining a better coordinated supply chain.

3. A General Supply Chain Model of the Electricity Industry

We consider several generators and retailers that trade their energy in a two-stage electricity market. At the first stage, generators sell their energy to retailers in a futures market through bilateral contracts. At the second stage, generators and retailers participate in a spot market in which the remaining of the energy is traded at a common price, the spot price. Finally, retailers sell the total energy purchased from generators to the final consumers.

The supply chain structure, represented in Fig.1 is the following: A) At time 1 and after a free negotiation process, generator i and retailer j agree to sign a bilateral contract in which generator i sells to retailer j an energy quantity q_{ij}^{F} at a price W_{ij}. At this time bilateral agreements can be established simultaneously between any generator i and any retailer j. This bilateral trading represents the interactions of a futures (forwards) market in which contracts are traded over the counter. B) At time 2, in the spot market each generator i sells an energy quantity q_i^{Sg} and each retailer j buys an energy quantity q_j^{Sr} at a common price, the spot price S. C) Finally, retailers sell the energy purchased at time 1 and time 2 to the final demand at a retail price P.

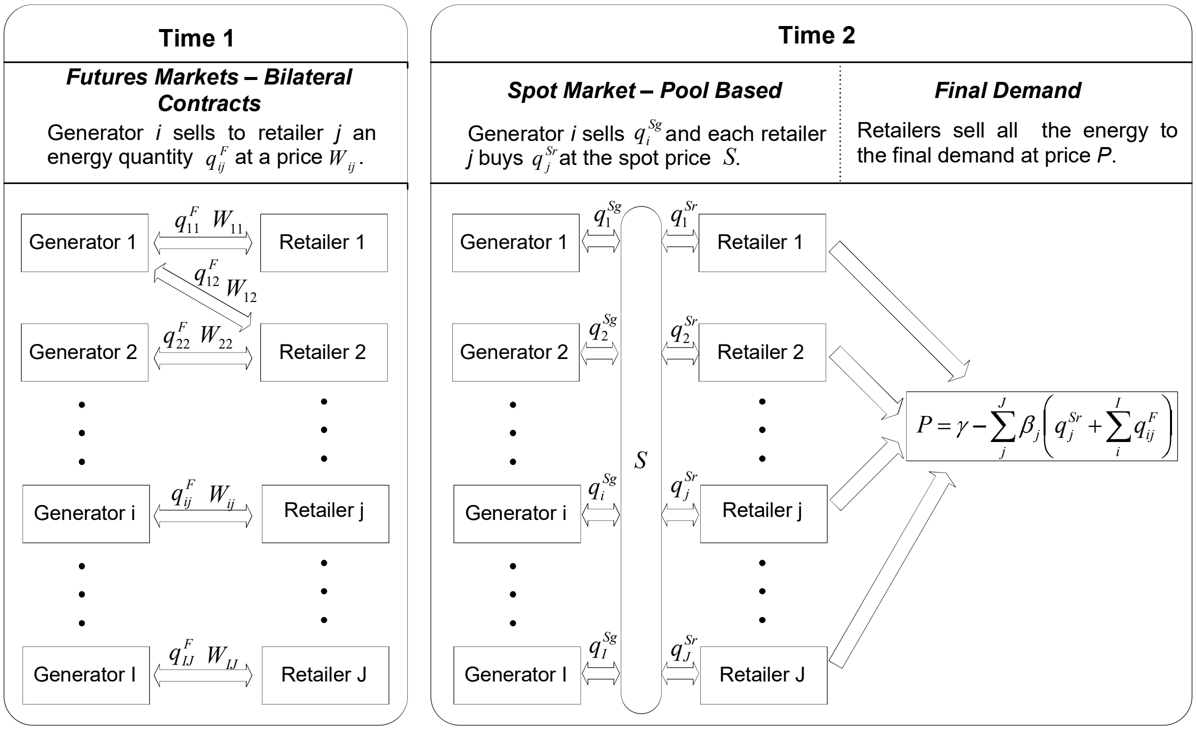

Fig. 1. Supply Chain Model

The total profit obtained by generator *i* from participating in the market is represented by (1), in which the first term stands for the total income from the futures market (bilateral contracts), i.e., the summation of energy quantity q_{ij}^F times bilateral prices W_{ij}. The second term corresponds to the income from the spot market, i.e., the energy quantity q_i^{Sg} times the spot price S. And the third term is the total production cost of generator *i* which is formulated as a quadratic function (conventional assumption for thermal generating units) where $c_i \geq 0$ for $i = 1,...,I$. Note that the total energy produced by a generator is the sum of the energy sold in the futures and spot markets.

$$\Pi_i^g = \sum_j^J q_{ij}^F W_{ij} + q_i^{Sg} S - a_i - b_i \left(\sum_j^J q_{ij}^F + q_i^{Sg} \right) - \frac{1}{2} c_i \left(\sum_j^J q_{ij}^F + q_i^{Sg} \right)^2 \quad i = 1,...,I. \quad (1)$$

Similarly, the total profit obtained by retailer *j* is represented by (2), in which the first term is the income from selling the energy purchased from the bilateral contracts $\left(\sum_i^I q_{ij}^F \right)$ and spot market (q_j^{Sr}) to the final consumers at a price *P*. The second term represents the cost of buying energy in the futures market, from generator *i*, at the prices W_{ij} and the third term is the cost of buying q_j^{Sr} in the spot market at a price *S*.

$$\Pi_j^r = P\left(q_j^{Sr} + \sum_i^I q_{ij}^F\right) - \sum_i^I q_{ij}^F W_{ij} - q_j^{Sr} S \qquad j = 1,\ldots,J \,. \tag{2}$$

Moreover, the retail price *P* is the result of consumers' preferences summarized in the linear inverse demand function (3) in which the conditions $\gamma \geq 0$, and $\beta_j \geq 0$ for $j = 1,\ldots,J$ are necessary to ensure that the demand curve is well behaved. Observe that the adoption of a linear demand curve constitutes an appropriate trade-off between the realistic representation of final consumers' behavior and the analytical tractability of the model. Furthermore, note that (3) considers a different slope β_j for each retailer. This is a generalization of the classical single-slope linear demand curve that allows us to distinguish between retailers.

$$P = \gamma - \sum_j^J \beta_j \left(q_j^{Sr} + \sum_i^I q_{ij}^F\right). \tag{3}$$

Equation (3) represents the consumers' linear demand function. Observe that since the market price *P* is the same, the consumers are indifferent to whether the energy they buy from retailer *j* have been previously traded in the futures market (q_{ij}^F) or in the spot market (q_j^{Sr}) and therefore the parameter β_j is the same. Additionally, the equilibrium condition for the spot market implies that the energy sold by generators must be equal to the energy bought by retailers in the spot market, i.e.,

$$\sum_i^I q_i^{Sg} = \sum_j^J q_j^{Sr} \,. \tag{4}$$

For clarity, the electricity transmission network is not explicitly considered, i.e., no electricity network constraint is assumed to be binding, which facilitates the derivation of analytical expressions.

It must be remarked that the futures market and the spot market are interrelated through equations (1), (2) and (3). Therefore, to analyze this two-stage market structure, we first determine the equilibrium in the spot market (time 2) considering that the bilateral contracts are already settled. This results in a spot market equilibrium that is parameterized in variables

q_{ij}^{F} and W_{ij}. Then we move backwards in time to analyze the bilateral contracts (time 1) in order to find the global equilibrium that characterizes the supply chain model.

4. Deriving the Supply Chain Equilibrium

Having described the general structure of the supply chain represented by our model, we now proceed to analyze its basic properties by solving its Nash equilibrium. The solution process begins in stage 2 (the spot market) and ends in stage 1 (the bilateral market).

Hence, let us start by analyzing the market equilibrium conditions at stage 2. At this stage the bilateral (futures) market has already finished, which means that the variables W_{ij} and q_{ij}^{F}, for $i = 1,...,I$ and $j = 1,...,J$, are considered parameters.

Each retailer should decide the optimal energy quantity q_{j}^{Sr} to buy in the spot market in order to maximize its profit from selling to the final consumers, by deriving the first order conditions (5).

$$\frac{\partial \Pi_{j}^{r}}{\partial q_{j}^{Sr}} = \frac{\partial P}{\partial q_{j}^{Sr}}\left(q_{j}^{Sr} + \sum_{i}^{I} q_{ij}^{F}\right) + P - S = 0 \qquad j = 1,...,J. \tag{5}$$

By combining the consumers' demand curve (3) and (5) we derive (6), which represents the relationship between the spot price and the energy quantities q_{j}^{Sr}, i.e., it stands for the retailers' demand curve in the spot market.

$$S = -\beta_{j}\left(q_{j}^{Sr} + \sum_{i}^{I} q_{ij}^{F}\right) + \gamma - \sum_{k}^{J} \beta_{k}\left(q_{k}^{Sr} + \sum_{i}^{I} q_{ik}^{F}\right) \qquad j = 1,...,J. \tag{6}$$

The Online Appendix A.1 provides details on how to combine (3) and (6) to establish the relationship between the spot price and the retail price (7), which does not depend on the future decisions. The retailers observe a demand function in the retail market, equation (3), and hence the dependence between the spot market price and the retail price is directly obtained from the equilibrium conditions of the spot market. A similar demand function has been used in, e.g., Allaz (1992), Allaz and Vila (1993), Herguera (2000), Le Coq and Orzen (2006), among others. This assumption is adopted for the sake of tractability.

$$P = \frac{\gamma}{J+1} + \frac{J}{J+1} S . \tag{7}$$

Considering equation (3) and (7), and assuming that $\sum_j^J \beta_j \left(q_j^{Sr} + \sum_i^I q_{ij}^F \right) \geq 0$ it can be shown that $P \geq S$ which means that, under the proposed framework, the retail price is always greater than or equal to the spot market price. Additionally, if J is sufficiently large, then it follows that $P \approx \frac{\gamma}{(J+1)} + S$, which indicates that as the number of retailers increases, the values of prices P and S get closer. Furthermore, the equilibrium condition (4) for the spot market can be combined with (A.4), i.e.,

$$\sum_j^J q_j^{Sr} = \sum_i^I q_i^{Sg} = \sum_j^J \left(\frac{\gamma - S}{(J+1)\beta_j} - \sum_i^I q_{ij}^F \right), \tag{8}$$

to allow deriving the aggregated demand curve faced by generators in the spot market (9), which represents the spot market price as function of the total generators production quantity in that market $\left(\sum_i^I q_i^{Sg} \right)$,

$$S = \gamma - B \sum_j^J \sum_i^I q_{ij}^F - B \sum_i^I q_i^{Sg} , \tag{9}$$

where $B = \frac{J+1}{\sum_j^J \frac{1}{\beta_j}}$. (10)

On the other hand, each generator decides the optimal quantity q_i^{Sg} to sell in the spot market. We assume that each generator maximizes its profit by taking into account the impact that its production has on the spot market through the demand function (9), i.e.,

$$\frac{\partial \Pi_i^g}{\partial q_i^{Sg}} = 0 = \frac{\partial S}{\partial q_i^{Sg}} q_i^{Sg} + S - b_i - c_i \left(q_i^{Sg} + \sum_j^J q_{ij}^F \right) \qquad i = 1,\ldots,I . \tag{11}$$

Including (9) into (11) and solving the resulting linear system of equations (as shown in Online Appendix A.2) renders:

$$q_i^{Sg} = \frac{\gamma - Rb_i + B\sum_m^I \frac{\sum_j^J c_m q_{mj}^F}{B + c_m} - Rc_i \sum_j^J q_{ij}^F - B\sum_m^I \sum_j^J q_{mj}^F + B\sum_m^I \frac{b_m}{B + c_m}}{R(B + c_i)} \quad i = 1,\ldots,I \tag{12}$$

which is the equilibrium quantity q_i^{Sg} sold in the spot market, where

$$R = 1 + B\sum_i^I \frac{1}{B + c_i}. \tag{13}$$

Note the dependency of (12) with the futures quantities q_{ij}^F, which are considered fixed at this stage of the analysis.

We can also replace (12) into (9), (9) into (7) and (9) into (A.4) to obtain the value at equilibrium of the spot variables S, P and q_j^{Sg} , respectively, as a function of the future quantities (q_{ij}^F). Note finally that the profit for both generators (1) and retailers (2) can be expressed as a function of the future decisions q_{ij}^F and W_{ij}, that is, $\Pi_i^g = f(q_{ij}^F, W_{ij})$ and $\Pi_j^r = g(q_{ij}^F, W_{ij})$.

Our analysis now continues with the calculation of the equilibrium conditions in the futures markets. The simultaneous maximization of generators and retailers individual profits characterizes the equilibrium in the futures market where the impact of the subsequent spot market is taken into account through the expressions derived for the spot market equilibrium.

The optimality conditions for each generator (14) and retailer (15) are derived from (1) and (2), respectively:

$$\frac{\partial \Pi_i^g}{\partial q_{ij}^F} = 0 = W_{ij} + \frac{\partial S}{\partial q_{ij}^F} q_i^{Sg} + S\frac{\partial q_i^{Sg}}{\partial q_{ij}^F} - b_i\left(\frac{\partial q_i^{Sg}}{\partial q_{ij}^F} + 1\right) - c_i\left(q_i^{Sg} + \sum_j^J q_{ij}^F\right)\left(\frac{\partial q_i^{Sg}}{\partial q_{ij}^F} + 1\right)$$

$$i = 1,\ldots,I. \quad j = 1,\ldots,J. \tag{14}$$

$$\frac{\partial \Pi_j^r}{\partial q_{ij}^F} = 0 = \frac{\partial P}{\partial q_{ij}^F}\left(q_j^{Sr} + \sum_i^I q_{ij}^F\right) + P\left(\frac{\partial q_j^{Sr}}{\partial q_{ij}^F} + 1\right) - W_{ij} - \frac{\partial S}{\partial q_{ij}^F} q_j^{Sr} - S\frac{\partial q_j^{Sr}}{\partial q_{ij}^F}$$

$$i = 1,...,I. \quad j = 1,...,J. \quad (15)$$

Considering equations (7), (9) and (12), and replacing the derivative terms (A.7)-(A.11) (Online Appendix A.3) into (14) and (15), we obtain a linear system of $2 \cdot I \cdot J$ equations with $2 \cdot I \cdot J$ variables (q_{ij}^F and W_{ij}) that characterizes the equilibria.

It is relevant to note that the bilateral negotiation process is implicitly modeled within equations (14) and (15). First, each generator *i* and retailer *j* determines by (14) and (15) the optimal energy quantity q_{ij}^F to sell and to buy, respectively, as a function of each price W_{ij}, i.e., its optimal offer and demand curves, and second, the market outcomes are derived as the joint solution of (14) and (15), which renders the production quantities and prices for which both generators and retailers maximize simultaneously their profit. In other words, system (14) plus (15) provides the futures market outcomes at equilibrium. Additionally, observe that since we implicitly consider the equilibrium in the spot market, the solution of system (14) plus (15) provides the two-stage market equilibrium for the supply chain model.

5. A General Supply Chain of Electricity Markets Considering Contracts

Considering the market framework in Section 3, we model the futures market by using two alternative types of bilateral contracts: contracts for differences and two-part tariff contracts. Our aim is to analyze the ability of contracts to mitigate market power via double marginalization and to analyze their impact on the proportions traded forward and spot.

5.1 Contracts for Differences

The structure of the supply chain with contracts for differences, is similar to the one depicted in Fig. 1., but now W_{ij} represents the strike price and q_{ij}^F represents a financial quantity, and it can be summarized as follows: A) At time 1, generator *i* and retailer *j* sign a bilateral contract for difference which consist of an energy amount, q_{ij}^F, and a strike price W_{ij}. B) At time 2, the spot market takes place in which each generator i sells an energy quantity q_i^{Sg} and each retailer *j* buys and energy quantity q_j^{Sr} at a common price, the spot price S. C) Finally, the retailers sell the energy traded in the spot market to the final consumers at a retail price, P.

Moreover, by definition of the contract for differences: A) If the price S is greater than W_{ij}, generator i pays retailer j the difference between these two prices times the amount of energy agreed in the contract, that is, $(S - W_{ij})q_{ij}^F$. B) If the price S is lower than W_{ij}, retailer j pays generator i the difference between these two prices times the amount of energy agreed in the contract, that is, $(W_{ij} - S)q_{ij}^F$.

By considering the contract for differences, the total profit obtained by the generators i is represented by equation (16) below. The main difference between (1) and (16) is that the later includes the term $\sum_j^J (W_{ij} - S)q_{ij}^F$ instead of $\sum_j^J W_{ij} q_{ij}^F$ to account for the income obtained from the contract for differences. Note that the total production is q_i^{Sg} since in this case q_{ij}^F is a financial quantity involving no physical delivery.

$$\Pi_i^g = q_i^{Sg} S + \sum_j^J (W_{ij} - S)q_{ij}^F - a_i - b_i q_i^{Sg} - \frac{1}{2} c_i \left(q_i^{Sg}\right)^2 \qquad i = 1,\ldots,I. \tag{16}$$

Similarly, by considering the contracts for differences, the total profit obtained by retailer *j* is formulated as (17), where the first term is the revenue from buying q_j^{Sr} in the spot market at a price *S* and selling it to the final consumers at a price *P*, and the second term corresponds to the income associated to the contract for difference.

$$\Pi_j^r = (P - S)q_j^{Sr} - \sum_{\mathrm{i}}^{\mathrm{I}} (W_{ij} - S)q_{ij}^F \qquad j = 1,\ldots,J. \tag{17}$$

The retailers' inverse demand function (18) is similar to (3) except that it does not include the financial quantity q_{ij}^F, and the new equilibrium condition for the spot market is (19).

$$P = \gamma - \sum_j^J \beta_j q_j^{Sr}. \tag{18}$$

$$\sum_i^I q_i^{Sg} = \sum_j^J q_j^{Sr}. \tag{19}$$

The derivation of the equilibrium solution for both the spot and futures market is similar to the procedure described in Section 3, and it is provided in Online Appendix B.

5.2. The Two-Part Tariffs Contract

The structure of the supply chain, including two-part tariff contracts is presented in Fig. 2. This supply chain structure can be summarized as follows: A) Generator *i* offers a bilateral two-part tariff to retailer *j* which is compound of a fixed fee F_{ij} plus its marginal generation cost times the energy purchased in the futures market, q_{ij}^F. B) At time 1, retailer *j* decides the quantity q_{ij}^F to buy from generator *i* knowing the components of the two-part tariff. C) At time 2, generators and retailers trade their energy in the spot market at a common price, the spot price S. D) Finally, retailers sell the energy purchased at time 1 and time 2 to the final consumers at a retail price P.

By considering two-part tariffs, and analogously to (1), the total profit obtained by generator *i* is provided by (20) and the total profit obtained by retailer *j* by (21), where T_{ij} is the two-part tariff paid by retailer *j* to generator *i*, which is defined by (22), in which the term in brackets is the marginal cost of generator *i*, i.e., the derivative of each generator's cost with respect to its total energy production $\sum_{j}^{J} q_{ij}^F + q_i^{Sg}$. Moreover, by considering the price imposed by the tariff (22), the equilibrium among retailers is characterized by the joint solution of system (described in equation C.5 of the Online appendix C), which provides the optimal future quantity q_{ij}^F to be bought by retailer *j* from generator *i*.

$$\Pi_i^g = \sum_{j}^{J} T_{ij} + q_i^{Sg} S - a_i - b_i \left(\sum_{j}^{J} q_{ij}^F + q_i^{Sg} \right) - \frac{1}{2} c_i \left(\sum_{j}^{J} q_{ij}^F + q_i^{Sg} \right)^2 \qquad i = 1, \ldots, I . \qquad (20)$$

$$\Pi_j^r = P \left(q_j^{Sr} + \sum_{i}^{I} q_{ij}^F \right) - \sum_{i}^{I} T_{ij} - q_j^{Sr} S \qquad j = 1, \ldots, J \qquad (21)$$

$$T_{ij} = F_{ij} + \left[b_i + c_i \left(\sum_{j}^{J} q_{ij}^F + q_i^{Sg} \right) \right] q_{ij}^F \qquad i = 1, \ldots, I. \quad j = 1, \ldots, J . \qquad (22)$$

In this model, the final consumer demand and the equilibrium conditions for the spot market are equations (3) and (4), respectively. The procedure followed to obtain the equilibrium conditions for both the spot and futures market is analogous to the one presented in Section 3, and it is presented in Online Appendix C.

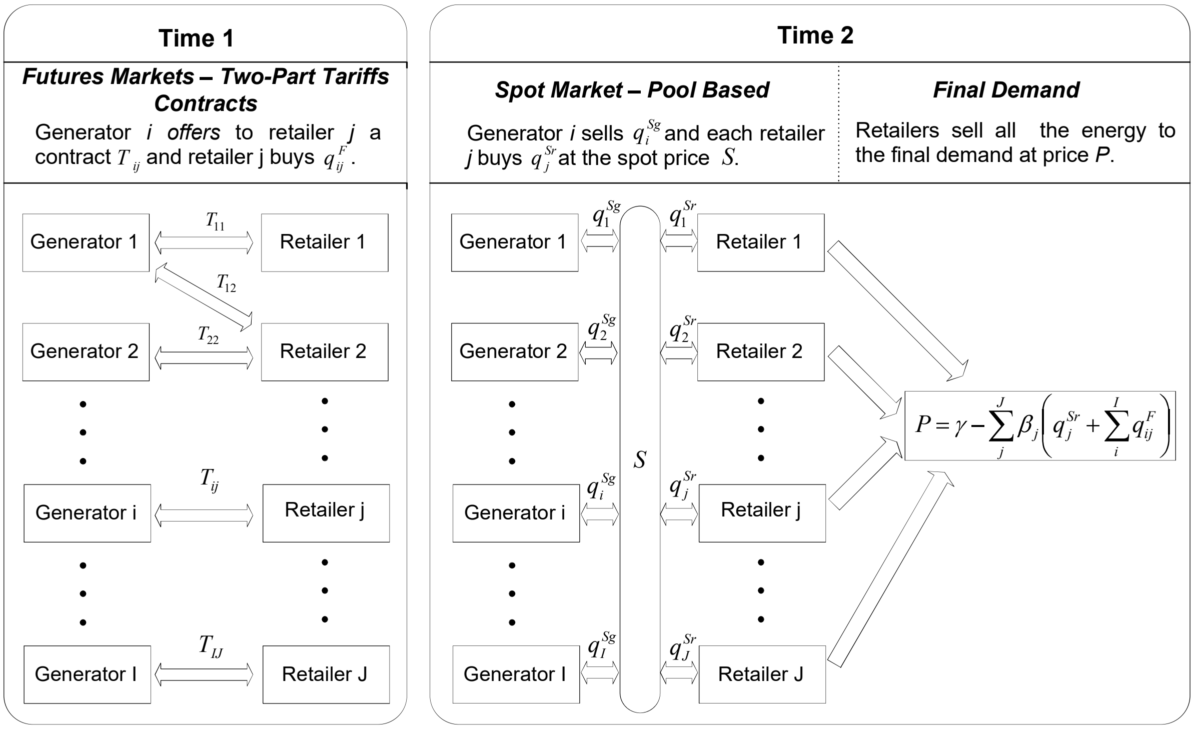

Fig 2. Two-Part Tariff Model

6. A Case Study about the Spanish Electricity Market

In this section we present the results of a case study based on the Spanish part of the Iberian electricity market, OMIE (2012), comparing the outcomes of the different market configurations presented in the previous sections. This case study aims to approximate the behavior of a real-world electricity market including several retailers, generators and final consumers. Basically, the Spanish market is formed by a combination of the two market structures described in Section 2.2, i.e, bilateral contracts and pool. The main features of the market are as follows. First, generators and retailers are allowed to sign physical bilateral contracts which are compound of an energy quantity, an energy price and a delivery date. Second, generators and retailers participate in a daily market (day-ahead market) in which the market operator matches electricity power selling offers and purchase bids to determine the market price as well as the production (consumption) energy quantities corresponding to each generator (retailer) for each hour in the schedule. Most of the energy is traded in the pool which represents around 90% of the total energy transactions.

In the analysis presented next we have considered the spot market results corresponding to one arbitrary day: May 12 2009, and hour 4:00 to 5:00 p.m., which are available at OMIE

(2012). The model parameters are tuned up to approximate those of the Spanish market. The procedure to tune up the parameters is described in detail in the following.

The Spanish part of the Iberian electricity market is characterized by presenting an oligopolistic structure where most of the energy trading occurs between a few number of dominant generators and dominant retailers. For instance, analyzing the markets shares of the producers and the retailers for the particular month under study (data available at OMIE, 2012) it can be observed that the three main generating companies (GAS NATURAL-FENOSA, ENDESA and IBERDROLA) in the Spanish market produced almost 60% of the total energy production. Similarly, for that same month, the purchases of energy made by four retailing companies (ENDESA, IBERDROLA, GAS-NATURAL FENOSA, and HIDROCANTÁBRICO) represented the 84% of the total purchases. Taking this into account, the number of oligopolistic producers in the model is set to 3 and the 40% remaining production is generated by a competitive producer-fringe. Likewise, the number of oligopsonistic retailers is 4 and the 16% remaining demand is supplied to the final consumers by a competitive retailer-fringe.

The producers' cost parameters are derived from the offer curves of the three main producers that participate in the Spanish part of the Iberian electricity market for the day under study (data available at OMIE, 2012). In the parameterization process we have adopted the following assumptions. First, we assume that the stepwise supply offer curve of each producer represents its true marginal cost. Second, we approximate this curve by a linear one that corresponds to the marginal cost derived from a quadratic cost function (the one considered in this paper). However, note that a linear curve can be a poor approximation of a stepwise supply function. Thus, in order to obtain a more realistic representation of the functioning of the market, the supply functions are linearly approximated in the neighborhood of the resulting equilibrium prices. Third, the values of b_i and c_i are set as the intersection with the y-axis and the slope of each linear cost function, respectively. Finally, cost parameters a_i are fixed to arbitrary values since they do not have a direct influence of the market results. Fig. 3 depicts the stepwise supply offer curves of each of these producers (solid line) and their corresponding linear approximations (dash line) in the neighbourhood of prices between 30 and 60 €/MWh (note that the resulting spot price of the day and hour under study is equal to 39 €/MWh, OMIE, 2012).

Considering the above we obtain that $a_1 = a_2 = a_3 = 0$, $b_1 = -92$, $b_2 = -192$, $b_3 = -90$, $c_1 = 0.019$, $c_2 = 0.04$, and $c_3 = 0.018$.

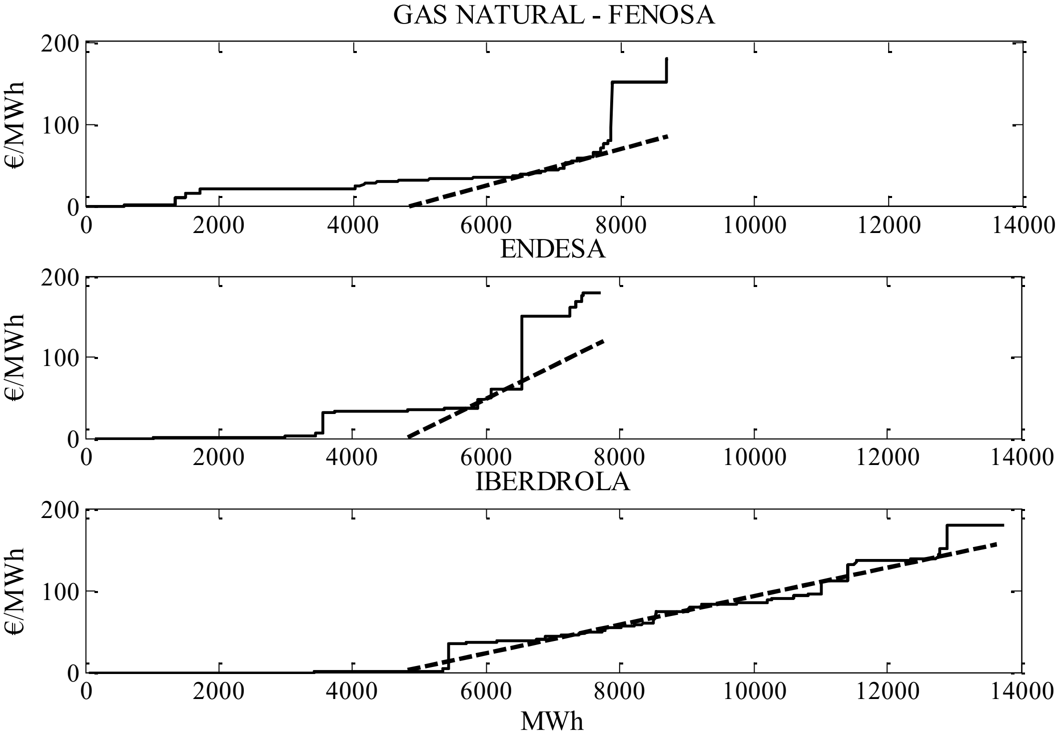

Fig. 3. OMIE Supply Curves of the Three Main Producers (12/05/2009, 4:00-5:00 p.m.).

Demand curve parameters: the demand curve parameters, γ and β_j, are estimated by approximating the aggregated stepwise demand curve of the four main retailer companies participation in the day under study (solid line in Fig. 4) by the spot market linear demand curve (9) (dash line in Fig.4). To eliminate the effect of futures markets in the linear approximation in Fig. 4, q_{ij}^F are considered equal to zero, and this approximation is also made in the neighbourhood of the resulting equilibrium prices. Then β_j is computed from (10) considering that *B* represents the slope of the linear demand curve (dash line in Fig. 4) and that all β_j are the same, i.e, $\beta_j = \beta \quad \forall j$. However, observe that our model considers different values of β_j per retailer. Therefore, using the estimated value β as a reference, the values of β_j are selected by a trial-and-error process so that the market share of each retailer is equivalent to those corresponding to the retailers market shares observed in May 2009, i.e., ENDESA 38%, IBERDROLA 26%, GAS NATURAL-FENOSA 29% and

HIDROCANTABRICO 7% (assuming that these four retailers are the only ones participating in the market). Finally, we obtain that $\beta_1 = 0.008$, $\beta_2 = 0.012$, $\beta_3 = 0.013$ and $\beta_4 = 0.017$.

Note that the demand slope faced by retailer 1 is the lowest while the one faced by retailer 4 is the highest. This can be interpreted as that the final consumers behave more inelastically when buying from retailer 4 than from retailer 1. The value of γ can be obtained as the interception between the linear demand curve and the y-axis.

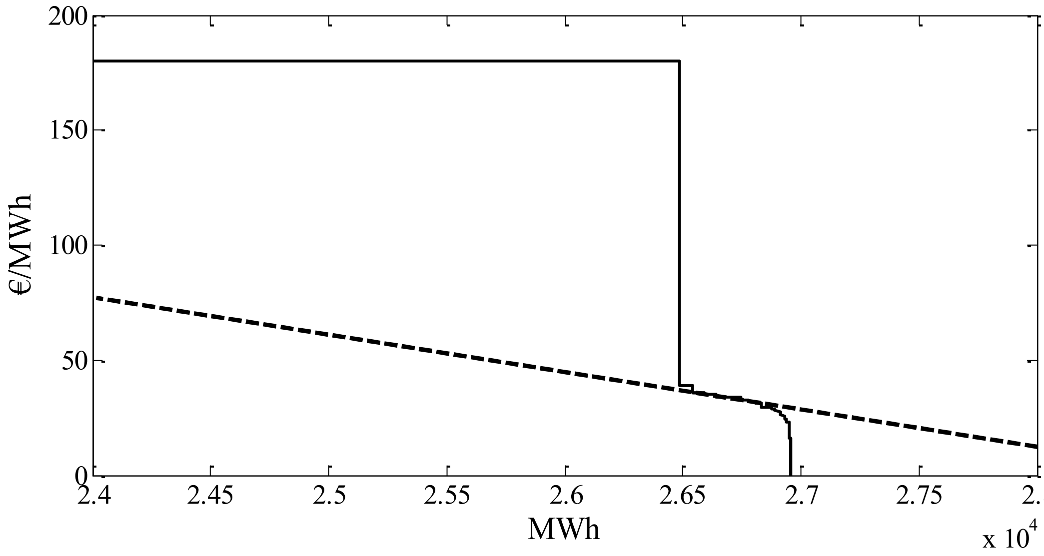

Fig. 4. OMIE Aggregate Demand Curve of the Four Main Retailers (12/05/2009, hour 5:00 p.m.).

In the case considered, the three oligopolistic companies produced around the 60% of the electricity traded in the market while the electricity purchased by the four oligopsonistic retailers represented about 84% of the total purchases. Therefore, in order to account for the activities of the competitive fringes (both retailers and generators) we remove 16% percent of the total demand (for every price) from the final consumers to the retailers (as this percentage is provided by the competitive retailer-fringe). Additionally, from the total demand from the retailers to the generators we need to remove 40% as this was generated by the competitive retailer-fringe. Consequently, in order to correct this energy mismatch between the retail and wholesale market we need to subtract 24% (i.e., 40%-16%) for every level of price, from the demand in the wholesale market. For this reason, the value of γ is set to a value so that the producers face their corresponding residual demand, i.e., γ is reduced to $\gamma - \beta Q$, where Q, represent the 24% of the total spot production observed in the day under study (OMIE 2012). This renders $\gamma = 330$.

The two-part tariff model is solved without assigning any specific value to the fixed fee F_{ij} . This allows us to drawn some conclusions regarding the appropriate values to assign to this parameter, considering that some of the market outcomes are parameterized in F_{ij} . Results corresponding to different market configurations are presented in Table 1. The second column in Table 1 provides the market outcomes for the general supply chain model described in Section 3. The third column corresponds to the contract for differences model of Subsection 5.1 whereas the two-part tariff (Subsection 5.2) results are provided in column 4.

Table 1. Trading in the Futures Market between Generator *i* and Retailer *j* (q_{ij}^F) in MWh.

q_{ij}^F	General Supply Chain	Contract for Differences	Two-Part Tariff
q_{11}^F	$-4557.30 + q_{22}^F + q_{23}^F + q_{24}^F + q_{32}^F + q_{33}^F + q_{34}^F$	$-4557.30 + q_{22}^F + q_{23}^F + q_{24}^F + q_{32}^F + q_{33}^F + q_{34}^F$	902.96
q_{12}^F	$3219.06 - q_{22}^F - q_{32}^F$	$3219.06 - q_{22}^F - q_{32}^F$	656.02
q_{13}^F	$3079.74 - q_{23}^F - q_{33}^F$	$3079.74 - q_{23}^F - q_{33}^F$	618.03
q_{14}^F	$2686.37 - q_{24}^F - q_{34}^F$	$2686.37 - q_{24}^F - q_{34}^F$	510.76
q_{21}^F	$4077.33 - q_{22}^F - q_{23}^F - q_{24}^F$	$4077.33 - q_{22}^F - q_{23}^F - q_{24}^F$	462.77
q_{22}^F	q_{22}^F	q_{22}^F	344.24
q_{23}^F	q_{23}^F	q_{23}^F	326.00
q_{24}^F	q_{24}^F	q_{24}^F	274.51
q_{31}^F	$4604.56 - q_{32}^F - q_{33}^F - q_{34}^F$	$4604.56 - q_{32}^F - q_{33}^F - q_{34}^F$	996.16
q_{32}^F	q_{32}^F	q_{32}^F	732.76
q_{33}^F	q_{33}^F	q_{33}^F	692.23
q_{34}^F	q_{34}^F	q_{34}^F	577.81
Total $\sum_{ij}^{IJ} q_{ij}^F$	13109.82	13109.82	7094.31

One first observation from Table 1 is that the solution of both the general supply chain and contract for differences models renders multiple equilibria in the futures market. This means that the values of quantities q_{ij}^F are not uniquely defined and form a subspace with some degrees of freedom. In particular, for the considered case study, the futures quantities q_{ij}^F for both the general supply chain and contract for differences models, have six degrees of freedom, i.e., the value of the variables q_{22}^F , q_{23}^F , q_{24}^F , q_{32}^F , q_{33}^F and q_{34}^F can be fixed without restrictions in order to obtain the value of other futures quantities (q_{11}^F , q_{12}^F , q_{13}^F , q_{14}^F , q_{21}^F and q_{31}^F). Nonetheless, from Table 1 we observe that the total energy sold by generator i $\left(\sum_j^J q_{ij}^F\right)$ and purchased by retailer j $\left(\sum_i^I q_{ij}^F\right)$, are uniquely determined.

The total quantities traded in the futures market ($\sum_{ij}^{IJ} q_{ij}^F$) for the general supply chain and contract for differences models are larger than for the two-part tariff contracts. This can be explained by considering the direct relationship between the energy traded and the two part-tariff variable fee (22). At time one, the more energy retailers buy in the futures, the more energy generators have to produce, which increases their marginal cost and, therefore, the two part-tariff variable fee rises. This is not convenient for the retailers because they have to buy the energy at higher prices. Therefore the equilibrium in the futures is reached at quantities lower than the other models. It should be noted that all models result in that the lower production cost a generator has, the higher energy quantity it sells in the futures market. Additionally, retailers buy more energy in the futures market as their associated demand slope β_j is lower.

Fig. 5 compares the quantities traded in the futures (grey area) with the ones traded in the spot markets (white area), for the different market structures considered. Observe that a similar behavior is observed in the spot market if compare with the futures market. However, in this case, the contract for differences model is the one that entails larger electricity transactions in the spot market. Observe that this is originated by the lack of a "physical" trading in the futures market which requires that all the production occurs in the spot market. It should be mentioned that the quantities traded in the only spot configuration are smaller than the total ones traded in the models that incorporate a futures market.

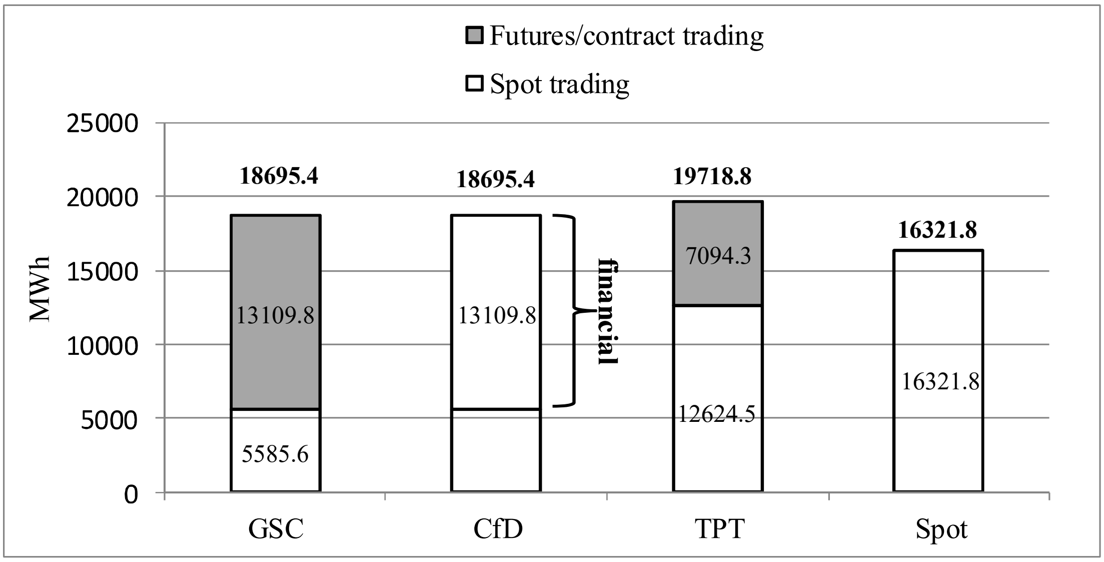

Fig 5. Production vs Quantities traded in the Spot and Futures Markets in the General Supply Chain (GSC), Contract for Differences (CdD), Two-Part Tariff (TPT) and Spot Only (Spot) Models.

Although the energy traded in the futures for the two-part tariff contract is the lowest among all the models, it results in the highest total production quantity (futures plus spot markets), which is caused by a high level of energy transactions in the spot. Note that this can be explained by considering the assumption made in our derivation in which $\frac{\partial T_{ij}}{\partial q_j^{Sr}} = 0$ (Online Appendix C), i.e., when the spot takes place, the retailers do not take into account the impact that the energy bought in the spot q_j^{Sr} may have on the tariff price. Retailers are then motivated to buy high amounts of energy in the spot to compensate the low level of energy purchased in the futures.

The spot trading results shown in Fig. 5, combined with the resulting high wholesale (S) and retail (P) prices, presented in Table 2, indicate that the only spot market organization favors the oligopolistic behavior of generators, i.e., they are able to reduce production in order to increase prices.

Regarding the futures market prices W_{ij}^F, it should be noticed that although the values of the future quantities q_{ij}^F are not uniquely defined (they form a subspace) for the general supply chain and the contract for differences models, the futures prices W_{ij}^F are uniquely determined as shown in Table 2. In this respect it should be remarked that each generator *i* sells its energy at a common price in the futures market, making no distinction among retailers.

Finally, note that all models proposed in this paper have in common that the prices of energy increase as the final delivery is closer in time, i.e., $W < S < P$. This is important since it allows retailers to achieve positive profits and to stay in business.

Table 2. Futures Market Prices (W_{ij}^{F}), Spot Market Price (*S*) and Retail Price (*P*) in €/MWh.

	General Supply Chain	Contract for Differences	Two-Part Tariff	Only Spot
Futures Price W_{1j}^{F}	54.19	54.19	-	-
Futures Price W_{2j}^{F}	55.78	55.78	-	-
Futures Price W_{3j}^{F}	54.06	54.06	-	-
Spot Price *S*	58.32	58.32	43.45	92.81
Retail Price *P*	112.66	112.66	100.76	140.25

As shown in Table 3, for the case in which there is only a spot market, generators obtain higher profits while retailers obtain lower ones if compared with the cases in which futures markets are considered. Note also that total profits, i.e., generators' + retailers' profits, are higher for the only spot market case.

Additionally, the generators' and retailers' profits corresponding to the two-part tariff model are a function of the fixed fee (F_{ij}): these fees can be fixed to values for which either the generators' or the retailers' profits are equal to the ones in the only spot case. This would guarantee that either the generators or the retailers are indifferent to the inclusion of two-part tariff contracts while ensuring that the resulting market prices are lower if compared with the only spot case. In particular, one interesting possibility is to compensate generators for their lack of market power in the futures market (they are forced to offer their tariff at their marginal costs) and fix their fees F_{ij} so that their profits are equal to the only spot case.

Table 3. Consumer Surplus and Profits per Type of Player and Market Structure, in €

	General Supply Chain	Contract for Differences	Two-Part Tariff	Only Spot
Prod. Profit Π_T^g	1888729.67	1888729.67	$\sum_{ij}^{IJ} F_{ij}$ +1629841.89	2409618.66
Ret. Profit Π_T^r	1064062.40	1064062.40	1164217.89-$\sum_{ij}^{IJ} F_{ij}$	774248.29
Total Profit $\Pi_T^g + \Pi_T^r$	2952792.07	2952792.07	2794059.79	3183866.95
Cons. Surplus	2031636.7	2031636.7	2260176.90	1548536.46

Furthermore, the less desirable market structure from the consumers' point of view is the spot market only, which results in higher prices and lower productions (effect of double marginalization) that render the lowest consumer surplus. On the other hand, the two-part tariff contract provides the largest consumer surplus as it presents the lowest prices and the largest total production.

Finally, the general supply chain model (Section 3) provides the same market outcomes as the contract for differences (Subsection 5.1) which is just a financial derivative. Furthermore, two-part tariff contracts (Subsection 5.2) results in even more competitive market outcomes (lower prices than the general supply chain model): this result does not depend on the selected fixed fee F_{ij} . On the other hand, considering only a spot market leads to higher wholesale and final prices that increase the generators' profit while decreasing the retailers' profit. We would like to stress that the major qualitative conclusions from our computational experiments, in this case study, are very robust.

7. Conclusions and Discussion

In this article we propose a model of the electricity supply chain that represents the interaction between final consumers, retailers and generators, taking into account the presence of bilateral contracts, futures and spot markets, and the possibility of supply chain coordination by using contracts for differences and two-part tariffs. We compute the Nash equilibrium of the electricity supply chain and, in the context of a case study in the Spanish electricity market, we compare how the existence of futures markets and the different type of contract influence the market equilibrium.

Our results suggest that the development of a futures market within the Spanish part of the Iberian electricity market would improve the efficiency of the electricity market, reducing double marginalization, and leading to lower retail prices, which supports Allaz and Vila's (1993) results.

Regarding the use of contracts to improve coordination and reduce double marginalization in the supply chain, we found that, in the context of the Spanish part of the Iberian electricity market, the contract for differences has no impact on the spot and retail prices as these are the same as in the general supply chain model. Nonetheless, the contract for differences has an important impact on the level of trading in the spot market, which increases substantially both in total and as a proportion of total trade. Moreover, we can also observe that there are important implications of the contract for differences on the retailers' profits as these depend on the electricity traded forward. The case with only spot markets is the one with the worst social optimum, having higher prices.

The two-part tariff contract leads to the lowest prices, the largest total production and the largest consumer surplus, representing the most efficient contract for improving coordination and reducing double marginalization. This result is consistent with Lantz (2009) in his analysis of the bilateral monopoly. However, it differs from the conclusions in: Majumder and Srinivasan (2006) and in Lau et al. (2008), both of which reported that, in the presence of a market leader, the two-part tariff increases profits; Ferrer et al. (2010) and Schlereth, et al. (2010) both of which explained that the presence of a fixed cost for consumers increases total consumption per product and the firms' profitability. The main explanation for the different results is the presence of market leadership, which seems to make the two-part tariff more profitable; likewise, if consumers have no other alternative, the presence of a subscription fee increases consumption and profits.

Finally, we found that, in general, our different models of the electricity supply chain do not have unique equilibria: a) in the general supply chain, considering or not contracts for differences, the quantities traded forward are undefined; b) in the two-part tariff model the fixed tariff to be paid is not defined, even though all the production and trading variables are uniquely defined.

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