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Paulo Coutinho
Universidade de Brasília

André Rossi de Oliveira
Universidade de Brasília

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DEPARTAMENTO DE ECONOMIA

Campus Universitário Darcy Ribeiro

Instituto Central de Ciências

Caixa Postal 04302, 70910-900 Brasília, DF, Brasil

Tel.: (55-61) 3072498, 2723548

Fax: (55-61) 3402311

E-mail: econ@unb.br

http://www.unb.br/ih/eco

SÉRIE DE TEXTOS PARA DISCUSSÃO

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Spot and Contract Markets in the Brazilian Wholesale Energy Market

Paulo Coutinho* and André Rossi de Oliveira⊥

The paper models the interaction between a contract and a spot market whose features are borrowed from the Brazilian Wholesale Energy Market. The spot market is modeled as a random mechanism that chooses quantity and prices of electricity. The contract market is composed of generators, retail suppliers of electricity and dealers. The generators and suppliers are price takers, while the dealers have market power. It is shown that, when the number of generators and suppliers increase, even if there is only a monopolist dealer in the market, the contract prices converge to the expected spot price. Moreover, the quantity of energy traded in the contract market approaches the total amount of energy available in the system when the number of dealers increases without bound.

1. Introduction

It is not an overstatement to say that, following the lead of the United Kingdom, some electricity systems around the world have undergone a revolution. After the British Electricity Act of 1989, a new electricity supply industry emerged in the United Kingdom that has served as a model for privatizations and restructurings of electricity sectors in countries like Norway, Sweden, Denmark, Argentina, United States and more recently Brazil.

Usually the restructuring starts with reorganization that institutes regulated common carriage in transmission and distribution, followed by the privatization of state-owned enterprises. Distribution to residential consumers initially remains a monopoly in most systems, but competition is supposed to take place in generation from the outset. Wholesale competition requires sales of electricity from generators to distribution companies, and consequently there must exist a market where electricity can be traded. Due to imbalances between contract amounts and actual flows of energy, which can only be assessed when meters are read, there is a need to set up a mechanism to ensure operational efficiency. In a competitive environment, the natural choice for such a mechanism is a spot market. The functioning of such spot markets has been extensively studied in the literature. For instance, Green and Newbery (1992), von der Fehr and Harbord (1993), Green (1996) and Wolfram (1998) study the Electricity Pool in England and Wales. Amundsen, Bergman et al. (1998) and Andersson and Bergman (1995) provide an analysis of the Nordic Power Exchange, and Moore and Anderson (1997) discuss the new arrangements in the California spot and contract markets.

* Department of Economics, University of Brasília.
⊥ Department of Economics, University of Brasília.

In Brazil, the Wholesale Energy Market was created in 1998, but its implementation has been gradual. It started in September 2000 and is expected to be completed by February 2002. This market has some peculiar features due to two atypical characteristics of the Brazilian system: (a) approximately 93% of generation is hydroelectric, and (b) many generation plants are located in the same river basin, producing externalities in cascade.

In a nutshell, the Brazilian Wholesale Market (MAE) is organized as follows. The Brazilian Electricity Regulatory Agency (ANEEL) determines the system firm energy, which is the amount of energy that can be generated by the system with 95% probability. This firm energy is allocated between the hydroelectric and flexible thermoelectric plants, and the firm energy allotted to a generator constitutes the ceiling to the quantity of electricity it can sell through contracts. The National System Operator (ONS) is in charge of dispatch, which is scheduled based on technical information provided by the generators (hydro and thermoelectric). An optimization algorithm to which this same technical information and estimates of demand for electricity are fed into calculates the value of water, which is the basis for the determination of the spot price. Thus, from the point of view of the agents in the market, the spot price is a random variable.

The difference between the quantity of energy a generator is instructed to generate and the quantity it sold forward is valued at the spot price. This means that generators are exposed to a spot price risk, which is more severe if they own hydroelectric plants, since they can end up producing less energy than their firm energy as a result of system optimization. In order to alleviate this problem, a mechanism of energy reallocation was created. Basically, it assigns to each generator a fraction of the actual electricity generated by hydroelectric plants in proportion to its share of the hydroelectric firm energy.

There is one feature of the organization of the Brazilian electricity market that is of particular interest for the study of contract markets. Every generator was required to sign initial contracts with distribution companies. These contracts specify fixed amounts of electricity to be delivered to the distribution companies until the year 2002. After 2002, those quantities will be reduced at a rate of 25% a year. This means that initially the contract market will have a relatively small size. After 2002, however, the contract market should flourish, and the increased quantity of energy available to be traded should entail the appearance of dealers in this market. As a matter of fact, this is already happening, albeit to a small scale. Generators are entering bilateral contracts with distribution companies to sell their energy surplus (in excess of what is specified in their initial contracts).

This paper models the electricity market in Brazil under the assumption that the contract market is mature enough to allow for the presence of dealers. The model pays special attention to the interaction between the contract and spot markets, and it does not try to account for the existence of an energy reallocation mechanism. Although it draws its main features from the Brazilian case, the model is of interest in its own, since it brings new elements to the analysis of contract markets, like the role played by dealers and a spot market where generators have no market power.

There are other papers in the literature that also aim at explaining the interface between spot and contract markets. Green (1999), for instance, investigates how the contract market in the UK works. In order to do that, he models the spot market using the theory of supply function equilibria developed in Klemperer and Meyer (1989). His main conclusion is that generators playing a Bertrand game set prices equal to marginal costs and cover all of their expected output in the contract market, while Cournot generators sell no contracts unless they can earn a hedging premium from selling to risk-averse buyers. The second part of this result is in contrast with Allaz and Vila (1993), who analyze the strategic link between the forward and the spot market. Their main objective is to provide a rationale for the existence of forward markets in the case of certainty and perfect foresight, and they show that firms (not necessarily generators, since they don't restrict their analysis to the electricity market) with Cournot conjectures do sell forward part of their production. This is corroborated by another model of contracting in the electricity industry, provided by Powell (1993). His main finding is that, when generators collude, futures prices will be above expected spot prices and hedging will be partial.

This paper differs from the literature mentioned above in two main respects. First, it does not allow generators to set quantities or submit supply schedules in the spot market. They also don't have any control over the spot price. Second, both generators and retail suppliers of electricity are supposed to behave competitively in the contract market, in contrast with the recent literature on futures and forward markets, which acknowledges that many commodities traded on those markets are not produced competitively. However, as was mentioned above, the generating sector of restructured electricity industries is supposed to be competitive after privatization takes place, and that is what this paper is trying to model. All the market power in the contract market belongs to the dealers, another novelty introduced by this paper.

The paper is organized as follows. Section 2 develops the basic framework of analysis and considers the case of a contract market with only one dealer. Section 3 extends the analysis to the case of many dealers playing a Cournot game. Section 4 concludes and the Appendix presents the main proofs.

2. Contract market with one dealer

The situation considered in this section is one where there are n generating companies (generators) and m electricity supply companies (suppliers), which are players in both the spot and contract markets, and one dealer in the contract market. A contract here is a forward contract that specifies a given quantity of electricity to be delivered in the future for a certain price. The generators are indexed by $k,\, k = 1,\ldots,n$, and the suppliers by $i,\, i = 1,\ldots,m$. All generators have the same technology and each one is assigned an amount of firm energy F_k by the regulator. All suppliers have the same technology and each one has to supply an amount of energy equal to R_i in the retail market. The first assumption made is that $R = F$, where $R = \sum_{i=1}^{m} R_i$ and $F = \sum_{k=1}^{n} F_k$. This means that the suppliers will sell all electricity generated. The spot market is modeled as a random mechanism, which yields a random spot price $\tilde{r}$. The contracts traded are forward contracts.

It is also assumed that both the generators and the suppliers have negative exponential utility functions $u(\pi) = -e^{-a\pi}$, where π is profit, and that $\tilde{r} \sim N\left(\mu_r, \sigma_r^2\right)$. The supplier's profit is given by

$$\pi_i^s = pR_i - \tilde{r}(R_i - y_i^s) - q^s y_i^s, \qquad (1)$$

where q^s is the price of a unit of contracted electricity as quoted by the dealer to the supplier, p is the fixed retail price of electricity and y_i^s is the quantity bought forward. One can immediately surmise that the suppliers are price takers in the contract, spot and retail markets.

The supplier's revenue is the amount of energy it sells times the retail price. Its cost includes the cost of buying energy in the spot market and the cost of buying it in the contract market. Notice that the quantity it buys in the spot market is the difference between how much electricity it has to sell and how much it buys through contracts. For simplicity, no account is taken of any other costs the supplier might incur.

The maximization problem of supplier i can be expressed in terms of the certainty equivalent measure, yielding:

$$\max pR_i - \overline{r}(R_i - y_i^s) - q^s y_i^s - \frac{a_i^s}{2} Var\left(pR_i - \tilde{r}(R_i - y_i^s) - q^s y_i^s\right), \qquad (2)$$

where $\overline{r}$ is the expected value of the spot price, and a_i^s is the supplier's coefficient of risk aversion.

The solution to this problem can be easily calculated:

$$y_i^s = \frac{\overline{r} - q^s + a_i^s R_i \sigma_r^2}{a_i^s \sigma_r^2} = \left(R_i + \frac{\overline{r}}{a_i^s \sigma_r^2}\right) - \frac{q^s}{a_i^s \sigma_r^2} = A_i - B_i q^s, \qquad (3)$$

where $A_i = R_i + \frac{\overline{r}}{a_i^s \sigma_r^2}$ and $B_i = \frac{1}{a_i^s \sigma_r^2}$. Notice that $A_i > 0$ and $B_i > 0$.

The generator is also a price taker in the contract and spot markets. Accordingly, his profit function is given by:

$$\pi_k^g = \tilde{r}(F_k - y_k^g) + q^g y_k^g - v_k F_k, \qquad (4)$$

where y_k^g is the quantity of output sold forward, q^g is the unit price of contracted electricity quoted by the dealer to the generator and v_k is the generator's (constant) marginal (and average) cost.

The generator's problem can then be represented as:

$$\max \overline{r}(F_k - y_k^g) + q^g y_k^g - v_k F_k - \frac{a_k^g}{2} Var\left(\tilde{r}(F_k - y_k^g) + q^g y_k^g - v_k F_k\right), \qquad (5)$$

where a_k^g is the generator's coefficient of risk aversion.

The solution to this problem is

$$y_k^g = \frac{q^g - \overline{r} + a_k^g \sigma_r^2 F_k}{a_k^g \sigma_r^2} = \left(F_k - \frac{\overline{r}}{a_k^g \sigma_r^2} \right) + \frac{q^g}{a_k^g \sigma_r^2} = C_k + D_k q^g , \tag{6}$$

where $C_k = F_k - \frac{\overline{r}}{a_k^g \sigma_r^2}$ and $D_k = \frac{1}{a_k^g \sigma_r^2}$. It can be easily seen that $D_k > 0$.

The dealer is a monopolist in the contract market. He quotes a selling price to the suppliers and a buying price to the generators. He is risk neutral and thus wants to maximize his profits, given by the spread $d = q^s - q^g$ times the quantity traded y. His problem is therefore:

$$\begin{aligned} &\max \left(q^s - q^g\right) y \\ &s.t. \quad q^s - q^g \geq 0, \end{aligned} \tag{7}$$

where $y = \sum_{i=1}^{m} y_i^s = \sum_{k=1}^{n} y_k^g$, i.e., total demand is equal to total supply of contracted electricity. From this last expression, one obtains

$$A - Bq^s = C + Dq^g, \tag{8}$$

where

$$A = \sum\nolimits_{i=1}^{m} A_i = R + \frac{\overline{r}}{\sigma_r^2} \sum\nolimits_{i=1}^{m} \left(a_i^s\right)^{-1}, B = \sum\nolimits_{i=1}^{m} B_i = \frac{1}{\sigma_r^2} \sum\nolimits_{i=1}^{m} \left(a_i^s\right)^{-1}, C = \sum\nolimits_{k=1}^{n} C_k =$$
$$= F - \frac{\overline{r}}{\sigma_r^2} \sum\nolimits_{k=1}^{n} \left(a_k^g\right)^{-1} \text{ and } D = \sum\nolimits_{k=1}^{n} D_k = \frac{1}{\sigma_r^2} \sum\nolimits_{k=1}^{n} \left(a_k^g\right)^{-1}.$$

The proposition below follows from the solution to (7). The main proofs are in the Appendix.

Proposition 1.1: The equilibrium quantities and prices in a contract market where (a) generators and suppliers are price takers, (b) the dealer has monopoly power, (c) all generators have the same technology and coefficient of risk aversion and (d) all suppliers have the same technology and coefficient of risk aversion, are given by:

$$q^s = \bar{r} + R\left(\frac{a_s\sigma_r^2}{2m}\right), \qquad q^g = \bar{r} - F\left(\frac{a_g\sigma_r^2}{2n}\right),$$
$$d = F\left(\frac{\sigma_r^2}{2}\right)\left(\frac{a_s}{m} + \frac{a_g}{n}\right), \quad y_i^s = R_i - \frac{R}{2m} \text{ and } y_k^g = F_k - \frac{F}{2n} \tag{9}$$

where $a_i^s = a_s \ \forall i = 1,\ldots,m$ *and* $a_k^g = a_g \ \forall k = 1,\ldots,n$.

Upon inspection, one can immediately see that the forward price of energy sold is lower than the expected spot price, while the price of energy bought is higher than the expected spot price. Accordingly, the energy contracted by generators is less than their firm energy and the energy contracted by supplier is less than their total retail sales.

The following corollary is an immediate consequence of the proposition.

Corollary 1.1. The equilibrium prices and quantities have the following properties:

(a) $\lim_{m\to\infty} q^s = \bar{r}$, q^s *is a decreasing function of* m *and an increasing function of* a_s, R and σ_r^2*;*

(b) $\lim_{n\to\infty} q^g = \bar{r}$, q^g *is an increasing function of* n *and a decreasing function of* a_g, F and σ_r^2*;*

(c) $\lim_{m,n\to\infty} d = 0$, d *is an increasing function of* a_s, a_g, F and σ_r^2*;*

(d) $\lim_{m\to\infty} y_i^s = 0$, $\lim_{n\to\infty} y_k^g = 0$ and $\lim_{m\to\infty} y = \lim_{n\to\infty} y = \frac{F}{2}$.

Proof: The only result that doesn't follow immediately from (9) is (d). First notice that $\lim_{m\to\infty} R_i = \lim_{n\to\infty} F_k = 0$, since R and F are fixed. This explains the first two limits. As for $\lim_{m\to\infty} y = \lim_{n\to\infty} y = \frac{F}{2}$, note that $y \equiv \sum_{k=1}^{n} y_k^g = \sum_{k=1}^{n}\left(F_k - \frac{F}{2n}\right)$ $= F - \frac{F}{2} = \frac{F}{2}$, i.e., y does not depend on n. Similarly, $y \equiv \sum_{k=1}^{n} y_i^s$ $= \sum_{k=1}^{n}\left(R_i - \frac{R}{2m}\right) = R - \frac{R}{2} = \frac{R}{2} = \frac{F}{2}$, which means that y does not depend on n either.

According to (a) and (b), the price paid by the dealer to the generators is increasing in the number of generators and the price charged to the suppliers is decreasing in the number of suppliers. This is a surprising result, since the dealer has a monopoly in the contract market. However, for a given volume of total firm energy (and energy sold by the suppliers), an increase in the number of generators means that each generator individually is exposed to less risk, since it has less energy to trade. Similarly, if the number of suppliers increases, each supplier individually faces less risk of being exposed to the spot price. In other words, the elasticity of demand for contracts increases because risk sharing is less important for generators and suppliers. In the limit, both prices go to the expected spot price.

The other findings reported in (a) and (b) are in line with the literature on forward and spot markets:

(i) The forward price paid by (to) a supplier (generator) is higher (lower) the more risk averse it is. This makes sense because a more risk-averse agent assigns more value to less exposure to the spot market.

(ii) The forward price paid by (to) a supplier (generator) is higher (lower) the larger the variance of the spot price. This larger variance is associated with more risk.

(iii) The forward price paid by (to) a supplier (generator) is higher (lower) the larger the total energy sales (firm energy). When the demand for energy (firm energy) is higher, each supplier (generator) individually has to trade more energy in the market, and this increases her risk of exposure.

The explanations given in (i), (ii) and (iii) are all based on the assumption that risk averse agents want to hedge against risk. In this model, they do that in the forward market, and any factor that increases the risk (of being exposed to the spot market) or makes the agent more risk averse increases its demand for hedging, affecting the forward price accordingly.

It is also possible to calculate the dealer's profit. Since half of the system's firm energy will be traded in the contract market, it can be calculated as $\pi_d = d\,y = F\left(\frac{\sigma_r^2}{2}\right)\left(\frac{a_s}{m}+\frac{a_g}{n}\right)\left(\frac{F}{2}\right) = F^2\left(\frac{\sigma_r^2}{4}\right)\left(\frac{a_s}{m}+\frac{a_g}{n}\right)$. One can immediately check that the dealer's profit decreases with m and n, being equal to 0 in the limit. This is exactly what one would expect after the discussion above, and it also agrees with the behavior of the dealer's spread, d, as reported in (c). The fact that the spread increases with the degree of risk aversion of generators and suppliers, with the variance of the spot price and with the system firm energy is a consequence of the behavior of q^s and q^g.

Perhaps even more startling than the results in (a) and (b) are the ones displayed in (d). The first one is only apparently disquieting. The fact that the quantity of energy hedged by each generator draws near to zero, and similarly for the supplier, while the total amount of energy traded in the contract market doesn't change, is easy to explain: the number of generators and suppliers is going to infinity. What is disturbing is that the size of the contract market doesn't change when the forward price to the generators is increasing and the forward price to the suppliers is decreasing at the same time (according to (a) and (b)). Under normal conditions, this would lead to an increase in the total amount of energy traded forward. The explanation for this apparent paradox is that, when the number of generators and suppliers increase, the spot market becomes more attractive. Each generator and supplier individually is exposed to less risk and, by trading in the spot market, gets a better price than that offered by the dealer. Therefore the size of the spot market does not diminish. In other words, the dealer does have a competitor, namely the spot market.

The next section discusses a model where there is more than one dealer.

3. Contract market with more than one dealer

According to Proposition 1.1, for a given number of generators and suppliers, the dealer will obtain a positive spread and, consequently, positive profits through its operations in the forward market. This should entice other firms to enter the market as dealers. The situation where there are many dealers in the market will be the focus of this section.

There are now *H* dealers, which play a Cournot game. Dealer *h's* profit function is $\pi_h = \left(q^d - q^g\right) y_h^d$, where y_h^d is the quantity of energy traded by dealer *h*. Dealer *h* has to solve the following problem, where $y \equiv \sum_{h=1}^{H} y_h^d$:

$$\begin{aligned} \max_{y_h} \quad & (q^s - q^g) y_h^d \\ s.t. \quad & y = A - Bq^s = C + Dq^g \end{aligned} \tag{10}$$

This problem is equivalent to

$$\max\left(\frac{A-y}{B} - \frac{y-C}{D}\right) y_h^d \tag{11}$$

where the restriction has already been included in the objective function.

Proposition 2.1: The equilibrium quantities and prices in a contract market where (a) generators and suppliers are price takers, (b) there are many dealers who play a Cournot game, (c) all generators have the same technology and coefficient of risk aversion and (d) all suppliers have the same technology and coefficient of risk aversion, are given by:

$$\begin{aligned} & q^s = \overline{r} + \left(\frac{R}{H+1}\right)\left(\frac{a_s \sigma_r^2}{m}\right), \quad q^g = \overline{r} - \left(\frac{F}{H+1}\right)\left(\frac{a_g \sigma_r^2}{n}\right), \\ & d = F\left(\frac{\sigma_r^2}{H+1}\right)\left(\frac{a_s}{m} + \frac{a_g}{n}\right), \quad y_i^s = R_i - \frac{R}{m(H+1)}, \\ & y_k^g = F_k - \frac{F}{n(H+1)}, \quad y_h^d = \frac{F}{H+1} \text{ and } y = \left(\frac{H}{H+1}\right) F \end{aligned} \tag{12}$$

Prices and quantities contracted by generators and suppliers display the same properties they displayed in Proposition 1.1. The total amount of electricity traded through forward contracts is less than the total amount of firm energy available.

This proposition is accompanied by the following corollary.

Corollary 2.1. The equilibrium prices and quantities have the following properties:

(a) $\lim_{m\to\infty} q^s = \lim_{H\to\infty} q^s = \overline{r}$, q^s *is a decreasing function of* m *and* H *and an increasing function of* a_s, R and σ_r^2*;*

(b) $\lim_{n\to\infty} q^g = \lim_{H\to\infty} q^g = \overline{r}$, q^g *is an increasing function of* n *and* H *and a decreasing function of* a_g, F and σ_r^2*;*

(c) $\lim_{m,n\to\infty} d = \lim_{H\to\infty} d = 0$, d *is an increasing function of* a_s, a_g, F and σ_r^2*;*

(d) y_i^s *and* y_k^g *are increasing functions of* H, $\lim_{m\to\infty} y_i^s = 0, \lim_{H\to\infty} y_i^s = R_i$ *and* $\lim_{n\to\infty} y_k^g = 0, \lim_{H\to\infty} y_k^g = F_k$*;*

(e) $\lim_{H\to\infty} y_h^d = 0$ and $\lim_{H\to\infty} y = F$.

Proof: Follows immediately from (12).

It is only worth commenting on the results from the corollary that are in addition to the analysis of the previous section. Nevertheless, it must be pointed out that, as one would expect, the results of Proposition 2.1 boil down to the results of Proposition 1.1 when we set $H = 1$.

Regarding (a), the new finding is that the forward price to the suppliers is a decreasing function of the number of dealers. That is exactly what a Cournot model should yield: the more dealers there are the stronger the competition between them, and this drives the price they charge the suppliers down. In the limit, they can charge no more than the expected spot price. A similar reasoning applies to (b), which says that the forward price the generators face is increasing in the number of dealers. This is also a consequence of the enhanced competition between dealers. In the limit, once again the expected spot price is achieved. That the spread will go to zero as the number of dealers increases without bound, as stated in (c), is a direct consequence of (a) and (b).

The new part in (d) refers to the behavior of the contracts held by generators and suppliers as the number of dealers increases. When that happens, the price paid by suppliers decreases and the price received by generators increases, approaching the expected spot price in the limit (as was seen in (a) and (b)). This in turn makes it more attractive for generators and suppliers to hedge in the contract market, and consequently their contracted energy approaches their firm energy (generators) and energy sales (suppliers).

Last but not least, part (e) shows that, as the number of dealers increases without bound, the size of the portfolio of each individual dealer shrinks to zero and the total amount of energy traded in the contract market moves toward the total amount of firm energy in the system. This is natural, since both generators and suppliers are individually trading almost all the energy they have or need in the contract market. In other words, the spot market becomes less of a competitor to the dealers, since generators and suppliers are exposed to the same spot price risk but now get better prices from them. This seems to indicate that the role played by the spot market tends to diminish due to increasing competition between dealers. It is worth stressing this last result: when the number of dealers increases, the tendency is for the spot market to shrink. This has serious consequences for any regulator concerned about setting up or overseeing the operation of an electricity market.

4. Concluding Remarks

The first main conclusion of the paper is that the price a supplier pays for each unit of electricity bought from a dealer in the contract market decreases as the number of suppliers increases. Similarly, the price a generator is paid by a dealer for a unit of electricity sold in the contract market goes up as the number of generators increases. In the limit, both prices move toward the expected spot price. This is a nonstandard result, since the dealer has monopoly power. It can be explained if one realizes that one of the main reasons agents enter contracts is to hedge against risk, in this case the risk of being exposed to the spot price. When the number of generators and suppliers increase, given the total amount of energy available in the system, each individual generator and supplier has less electricity to trade, and therefore less potential exposure to the spot market. This, in turn, means that risk sharing becomes less important to them, and dealers have to face competition from the spot market, diluting their market power. This is an issue that, despite of its importance to restructured electricity systems, where supposedly generation is competitive, is not addressed in the literature. For instance, Green (1999), Allaz and Vila (1993) and Powell (1993), all model the generating sector as a duopoly. As for the demand side of the contract market, Green (1999) supposes that the buyers determine the market-clearing price, Powell (1993), that they set quantities, and Allaz and Vila (1993) models them as speculators.

The second main conclusion is that the size of the contract market doesn't change when forward prices change in a way that favors generators and suppliers. Normally there would be an increase in the total amount of energy traded forward, but here the change in forward prices is a consequence of the increase in the number of generators and suppliers, making the spot market more attractive. To be more precise, as the total number of generators and suppliers increase, each one becomes less exposed to risk and, by trading in the spot market, gets a better price than that offered by the dealer. This means that the dealer has to face a serious competitor, namely the spot market, and this explains why the contract market doesn't expand.

Finally, the total amount of energy traded in the contract market approaches the system firm energy when the number of dealers increases without bound. This is a consequence of the fact that generators and suppliers are exposed to the same spot price risk but now get better prices in the contract market. This means that possibly the spot market becomes less important when there is increased competition between dealers. This is something the regulator should be concerned with.

The next step towards a full characterization of the Brazilian Wholesale Energy Market is to allow for agents to trade intertemporally. This is an important feature since the intertemporal discount rate of the National System Operator may be different from that of a generator. However, any attempt in that direction will have to face the challenge of keeping the intertemporal nature of the model while satisfying the restriction that the total amount of contracted energy cannot exceed the generator's firm energy, as required by the Brazilian market rules.

5. Appendix

Proof of Proposition 1.1:

Condition (8) can be used to rewrite the dealer's problem (7) as

$$\begin{aligned}&\max\left(\frac{A-C}{B}-\frac{D}{B}q^{g}-q^{g}\right)(C+Dq^{g})\\&s.t.\quad q^{s}-q^{g}\geq 0\end{aligned}\qquad (13)$$

The problem will be first solved without taking into account the restriction. Next it will be shown that the restriction is satisfied at the optimum.

First of all, it can be easily seen that the objective function is concave. In fact,

$$\begin{aligned}F(q^{g})&=\left(\frac{A-C}{B}-\frac{D}{B}q^{g}-q^{g}\right)(C+Dq^{g})=\frac{(A-C)C}{B}+\\&+\frac{(A-C)D}{B}q^{g}-\frac{DC}{B}q^{g}-\frac{D^{2}}{B}(q^{g})^{2}-Cq^{g}-D(q^{g})^{2},\end{aligned}$$

and, since $D>0,\ B>0$,

$$\begin{aligned}\frac{\partial F}{\partial q^{g}}&=\frac{(A-C)D}{B}-\frac{DC}{B}-\frac{2D^{2}}{B}q^{g}-C-2Dq^{g}\\\frac{\partial^{2}F}{\partial (q^{g})^{2}}&=\frac{-2D^{2}}{B}-2D<0.\end{aligned}$$

Thus the first order condition is both necessary and sufficient for a maximum. The first order condition for this problem is given by

$$\begin{aligned}&\left(-\frac{D}{B}-1\right)(C+Dq^{g})+\left(\frac{A-C}{B}-\frac{D}{B}q^{g}-q^{g}\right)D=0\\&\Rightarrow -\frac{DC}{B}-\frac{D^{2}q^{g}}{B}-C-Dq^{g}+\frac{AD-CD}{B}-\frac{D^{2}q^{g}}{B}-Dq^{g}=0\\&\Rightarrow \frac{2D^{2}q^{g}}{B}+2Dq^{g}+\frac{DC+BC-AD+DC}{B}=0\\&\Rightarrow \frac{2D^{2}}{B}q^{g}+2Dq^{g}+\frac{2DC+BC-AD}{B}=0\end{aligned}$$

This equation can be solved to obtain

$$q^g = -\frac{2DC + BC - AD}{B\left(\frac{2D^2}{B} + 2D\right)} = \frac{AD - C(2D+B)}{2D(D+B)} \tag{14}$$

and

$$\begin{aligned} q^s &= \frac{A-C}{B} - \frac{D}{B}\left(\frac{AD - C(2D+B)}{2D(D+B)}\right) = \frac{A-C}{B} - \frac{AD - C(2D+B)}{2B(D+B)} \\ &= \frac{2(A-C)(D+B) - AD + C(2D+B)}{2B(D+B)} = \frac{AD + 2AB - BC}{2B(D+B)} \\ &= \frac{AD + B(2A-C)}{2B(D+B)} \end{aligned} \tag{15}$$

The condition $q^g \le q^s$ is satisfied if

$$\frac{AD - C(2D+B)}{2D(D+B)} \le \frac{AD + B(2A-C)}{2B(D+B)}$$

Since $B > 0 \text{ and } D > 0$, this is equivalent to

$$\begin{aligned} &\left[AD - C(2D+B)\right]B \le \left[AD + B(2A-C)\right]D \\ &\Leftrightarrow ABD - 2BCD - CB^2 < AD^2 + 2ABD - BCD \\ &\Leftrightarrow ABD + BCD + AD^2 + CB^2 > 0, \end{aligned}$$

Now the simplifying assumption that all generators have the same coefficient of risk aversion, i.e. $a_k^g = a_g \ \forall k = 1,\ldots,n$, and that all suppliers also have the same coefficient of risk aversion, i.e. $a_i^s = a_s \ \forall i = 1,\ldots,m$, will be added. Then $A = R + \frac{m\overline{r}}{a_s\sigma_r^2}$, $B = \frac{m}{a_s\sigma_r^2}$, $C = F - \frac{n\overline{r}}{a_g\sigma_r^2}$, $D = \frac{n}{a_g\sigma_r^2}$ and, using $R = F$,

$$ABD + CBD + AD^2 + CB^2 = 2R\frac{m}{a_s\sigma_r^2}\frac{n}{a_g\sigma_r^2} + \left[\frac{m\overline{r}}{a_s\sigma_r^2} - \frac{n\overline{r}}{a_g\sigma_r^2}\right]\frac{m}{a_s\sigma_r^2}\frac{n}{a_g\sigma_r^2} +$$

$$+\left(R + \frac{m\overline{r}}{a_s\sigma_r^2}\right)\left(\frac{n}{a_g\sigma_r^2}\right)^2 + \left(R - \frac{n\overline{r}}{a_g\sigma_r^2}\right)\left(\frac{m}{a_s\sigma_r^2}\right)^2$$

$$= 2R\frac{m}{a_s\sigma_r^2}\frac{n}{a_g\sigma_r^2} + \frac{m\overline{r}}{a_s\sigma_r^2}\frac{m}{a_s\sigma_r^2}\frac{n}{a_g\sigma_r^2} - \frac{n\overline{r}}{a_g\sigma_r^2}\frac{m}{a_s\sigma_r^2}\frac{n}{a_g\sigma_r^2} +$$

$$+R\left(\frac{n}{a_g\sigma_r^2}\right)^2 + \left(\frac{m\overline{r}}{a_s\sigma_r^2}\right)\left(\frac{n}{a_g\sigma_r^2}\right)^2 + R\left(\frac{m}{a_s\sigma_r^2}\right)^2 - \left(\frac{n\overline{r}}{a_g\sigma_r^2}\right)\left(\frac{m}{a_s\sigma_r^2}\right)^2$$

$$= 2R\frac{m}{a_s\sigma_r^2}\frac{n}{a_g\sigma_r^2} + R\left(\frac{n}{a_g\sigma_r^2}\right)^2 + R\left(\frac{m}{a_s\sigma_r^2}\right)^2 > 0$$

Therefore, the restriction is satisfied at the optimum.

Condition (14) can now be expressed as

$$q^g = \frac{\left(R + \frac{m\overline{r}}{a_s\sigma_r^2}\right)\left(\frac{n}{a_g\sigma_r^2}\right) - \left(F - \frac{n\overline{r}}{a_g\sigma_r^2}\right)\left(\frac{2n}{a_g\sigma_r^2} + \frac{m}{a_s\sigma_r^2}\right)}{2\left(\frac{n}{a_g\sigma_r^2}\right)\left[\frac{n}{a_g\sigma_r^2} + \frac{m}{a_s\sigma_r^2}\right]}$$

$$= \frac{\frac{Rn}{a_g\sigma_r^2} + \frac{mn\overline{r}}{a_s a_g\left(\sigma_r^2\right)^2} - \frac{2Fn}{a_g\sigma_r^2} - \frac{Fm}{a_s\sigma_r^2} + \frac{2n^2\overline{r}}{a_g^2\left(\sigma_r^2\right)^2} + \frac{mn\overline{r}}{a_s a_g\left(\sigma_r^2\right)^2}}{2\left(\frac{n}{a_g\sigma_r^2}\right)\left[\frac{n}{a_g\sigma_r^2} + \frac{m}{a_s\sigma_r^2}\right]}$$

$$= \frac{-\frac{Fn}{a_g\sigma_r^2} - \frac{Fm}{a_s\sigma_r^2} + \frac{2mn\overline{r}}{a_s a_g\left(\sigma_r^2\right)^2} + \frac{2n^2\overline{r}}{a_g^2\left(\sigma_r^2\right)^2}}{2\left(\frac{n}{a_g\sigma_r^2}\right)\left[\frac{n}{a_g\sigma_r^2} + \frac{m}{a_s\sigma_r^2}\right]}$$

$$= \frac{-F\left(\frac{n}{a_g\sigma_r^2} + \frac{m}{a_s\sigma_r^2}\right)}{2\left(\frac{n}{a_g\sigma_r^2}\right)\left[\frac{n}{a_g\sigma_r^2} + \frac{m}{a_s\sigma_r^2}\right]} + \frac{\frac{2n\overline{r}}{a_g\sigma_r^2}\left(\frac{m}{a_s\sigma_r^2} + \frac{n}{a_g\sigma_r^2}\right)}{2\left(\frac{n}{a_g\sigma_r^2}\right)\left[\frac{n}{a_g\sigma_r^2} + \frac{m}{a_s\sigma_r^2}\right]}$$

$$= \overline{r} - F\left(\frac{a_g\sigma_r^2}{2n}\right) \tag{16}$$

Similarly, (15) can be expressed as

$$q^s = \frac{\left(R + \frac{m\overline{r}}{a_s\sigma_r^2}\right)\left(\frac{n}{a_g\sigma_r^2}\right) + \left(\frac{m}{a_s\sigma_r^2}\right)\left(2R + \frac{2m\overline{r}}{a_s\sigma_r^2} - F + \frac{n\overline{r}}{a_g\sigma_r^2}\right)}{\left(\frac{2m}{a_s\sigma_r^2}\right)\left(\frac{n}{a_g\sigma_r^2} + \frac{m}{a_s\sigma_r^2}\right)}$$

$$= \frac{\frac{Fn}{a_g\sigma_r^2} + \frac{mn\overline{r}}{a_s a_g\left(\sigma_r^2\right)^2} + \frac{Fm}{a_s\sigma_r^2} + \frac{2m^2\overline{r}}{a_s^2\left(\sigma_r^2\right)^2} + \frac{mn\overline{r}}{a_s a_g\left(\sigma_r^2\right)^2}}{\left(\frac{2m}{a_s\sigma_r^2}\right)\left(\frac{n}{a_g\sigma_r^2} + \frac{m}{a_s\sigma_r^2}\right)}$$

$$= \frac{F\left(\frac{n}{a_g\sigma_r^2} + \frac{m}{a_s\sigma_r^2}\right)}{\left(\frac{2m}{a_s\sigma_r^2}\right)\left(\frac{n}{a_g\sigma_r^2} + \frac{m}{a_s\sigma_r^2}\right)} + \frac{\frac{2m\overline{r}}{a_s\sigma_r^2}\left(\frac{n}{a_g\sigma_r^2} + \frac{m}{a_s\sigma_r^2}\right)}{\left(\frac{2m}{a_s\sigma_r^2}\right)\left(\frac{n}{a_g\sigma_r^2} + \frac{m}{a_s\sigma_r^2}\right)} = \overline{r} + F\left(\frac{a_s\sigma_r^2}{2m}\right) \qquad (17)$$

The combination of (3) with (17) and (6) with (16) yields:

$$\begin{aligned} y_i^s &= R_i + \frac{\overline{r}}{a_s\sigma_r^2} - \left(\frac{1}{a_s\sigma_r^2}\right)\left(\overline{r} + R\left(\frac{a_s\sigma_r^2}{2m}\right)\right) \\ &= R_i + \frac{\overline{r}}{a_s\sigma_r^2} - \frac{\overline{r}}{a_s\sigma_r^2} - \frac{R}{2m} \\ &= R_i - \frac{R}{2m} \end{aligned}$$

and

$$\begin{aligned} y_k^g &= F_k - \frac{\overline{r}}{a_g\sigma_r^2} + \frac{1}{a_g\sigma_r^2}\left(\overline{r} - F\left(\frac{a_g\sigma_r^2}{2n}\right)\right) \\ &= F_k - \frac{\overline{r}}{a_g\sigma_r^2} + \frac{\overline{r}}{a_g\sigma_r^2} - \frac{F}{2n} \\ &= F_k - \frac{F}{2n} \end{aligned}$$

Finally, the spread can be calculated as

$$
\begin{aligned}
d = q^{s} - q^{g} &= \overline{r} + F\left(\frac{a_s \sigma_r^2}{2m}\right) - \overline{r} + F\left(\frac{a_g \sigma_r^2}{2n}\right) \\
&= F\left(\frac{\sigma_r^2}{2}\right)\left(\frac{a_s}{m} + \frac{a_g}{n}\right)
\end{aligned}
$$

If the generators are symmetric, that is $F_k = \frac{F}{n}\ \forall k$, then $y_k^g = \frac{F}{n} - \frac{F}{2n} = \frac{F}{2n}$. Similarly, if the suppliers are symmetric, i.e. $R_i = \frac{R}{m}\ \forall i$, then $y_i^d = \frac{R}{m} - \frac{R}{2m} = \frac{R}{2m}$.

Proof of Proposition 2.1:

Problem (11) can be expressed as

$$
\max_{y_h^d} \left(\frac{AD + BC - (D+B)y}{BD}\right) y_h^d \tag{18}
$$

The first order condition for this problem is:

$$
\begin{aligned}
& -\frac{(D+B)}{BD} y_h^d + \frac{AD + BC - (D+B)y}{BD} = 0 \\
& \Rightarrow -(D+B)y_h^d + AD + BC - (D+B)y_h^d - (D+B)\sum_{j \neq h} y_j^d = 0 \\
& \Rightarrow y_h^d \left(2(D+B)\right) = AD + BC - (D+B)\sum_{j \neq h} y_j^d \\
& \Rightarrow y_h^d = \frac{AD + BC}{2(D+B)} - \frac{\sum_{j \neq h} y_j^d}{2}
\end{aligned} \tag{19}
$$

Since the dealers are symmetric, $y_h^d = \frac{y}{H}$ and $\sum_{j \neq h} y_j^d = \frac{(H-1)y}{H}$. Therefore

$$\begin{aligned}
y_h^d &= \frac{AD+BC}{2(D+B)} - \frac{(H-1)y}{2H} \\
\Rightarrow y &= \frac{H(AD+BC)}{2(D+B)} - \frac{H(H-1)y}{2H} \\
\Rightarrow y + \frac{(H-1)}{2}y &= \frac{H(AD+BC)}{2(D+B)} \\
\Rightarrow y &= \left[\frac{H(AD+BC)}{2(D+B)}\right]\left[\frac{2}{H+1}\right] = \frac{H(AD+BC)}{(H+1)(D+B)} \\
\text{and } y_h^d &= \frac{AD+BC}{(H+1)(D+B)}
\end{aligned} \tag{20}$$

As was done in the proof of Proposition 1.1, A, B, C and D can be substituted for in (20), generating

$$\begin{aligned}
y_h^d &= \frac{\left(R + \frac{m\overline{r}}{a_s\sigma_r^2}\right)\frac{n}{a_g\sigma_r^2} + \frac{m}{a_s\sigma_r^2}\left(F - \frac{n\overline{r}}{a_g\sigma_r^2}\right)}{(H+1)\left(\frac{n}{a_g\sigma_r^2} + \frac{m}{a_s\sigma_r^2}\right)} \\
&= \frac{\frac{Rn}{a_g\sigma_r^2} + \frac{mn\overline{r}}{a_s a_g\left(\sigma_r^2\right)^2} + \frac{Fm}{a_s\sigma_r^2} - \frac{mn\overline{r}}{a_s a_g\left(\sigma_r^2\right)^2}}{(H+1)\left(\frac{n}{a_g\sigma_r^2} + \frac{m}{a_s\sigma_r^2}\right)} \\
&= \frac{F\left(\frac{m}{a_s\sigma_r^2} + \frac{n}{a_g\sigma_r^2}\right)}{(H+1)\left(\frac{n}{a_g\sigma_r^2} + \frac{m}{a_s\sigma_r^2}\right)} = \frac{F}{H+1} \quad \text{and } y = \left(\frac{H}{H+1}\right)F,
\end{aligned} \tag{21}$$

where the fact that $R = F$ was used.

The next step is to calculate the prices:

$$\begin{aligned}
q^s &= \frac{A-y}{B} = \frac{R + \frac{m\overline{r}}{a_s\sigma_r^2} - \left(\frac{H}{H+1}\right)F}{\frac{m}{a_s\sigma_r^2}} \\
&= \frac{Ra_s\sigma_r^2}{m} + \overline{r} - \left(\frac{H}{H+1}\right)\left(\frac{a_s\sigma_r^2}{m}\right)F = \overline{r} + F\left(\frac{a_s\sigma_r^2}{m}\right)\left(\frac{1}{H+1}\right)
\end{aligned} \tag{22}$$

and

$$q^g = \frac{y-C}{D} = \frac{\left(\frac{H}{H+1}\right)F - F + \frac{n\overline{r}}{a_g\sigma_r^2}}{\frac{n}{a_g\sigma_r^2}}$$
$$= \frac{\frac{n\overline{r}}{a_g\sigma_r^2} - \left(\frac{1}{H+1}\right)F}{\frac{n}{a_g\sigma_r^2}} = \overline{r} - F\left(\frac{a_g\sigma_r^2}{n}\right)\left(\frac{1}{H+1}\right) \tag{23}$$

The spread can now be easily obtained:

$$s = q^s - q^g = \overline{r} + F\left(\frac{a_s\sigma_r^2}{m}\right)\left(\frac{1}{H+1}\right) - \overline{r} + F\left(\frac{a_g\sigma_r^2}{n}\right)\left(\frac{1}{H+1}\right)$$
$$= F\left(\frac{\sigma_r^2}{H+1}\right)\left(\frac{a_s}{m} + \frac{a_g}{n}\right)$$

Now (3), (6), (22) and (23) can be used to get

$$y_k^g = F_k - \frac{\overline{r}}{a_g\sigma_r^2} + \frac{1}{a_g\sigma_r^2}\left(\overline{r} - F\left(\frac{a_g\sigma_r^2}{n}\right)\left(\frac{1}{H+1}\right)\right)$$
$$= F_k - \frac{\overline{r}}{a_g\sigma_r^2} + \frac{\overline{r}}{a_g\sigma_r^2} - \frac{F}{n(H+1)} = F_k - \frac{F}{n(H+1)} \tag{24}$$

and

$$y_i^d = R_i + \frac{\overline{r}}{a_s\sigma_r^2} - \frac{1}{a_s\sigma_r^2}\left(\overline{r} + R\left(\frac{a_s\sigma_r^2}{m}\right)\left(\frac{1}{H+1}\right)\right)$$
$$= R_i + \frac{\overline{r}}{a_s\sigma_r^2} - \frac{\overline{r}}{a_s\sigma_r^2} - \frac{R}{m(H+1)} = R_i - \frac{R}{m(H+1)} \tag{25}$$

Finally, y can be calculated in three different ways:

$$\sum_{k=1}^{n} y_k^g = \sum_{k=1}^{n}\left(F_k - \frac{F}{n(H+1)}\right) = F - \frac{F}{H+1} = \left(\frac{H}{H+1}\right)F$$

$$\sum_{i=1}^{m} y_i^s = \sum_{i=1}^{m}\left(R_i - \frac{R}{m(H+1)}\right) = R - \frac{R}{H+1} = \left(\frac{H}{H+1}\right)R$$

$$\sum_{h=1}^{H} y_h^d = \sum_{h=1}^{H}\frac{F}{H+1} = \left(\frac{H}{H+1}\right)F$$

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