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ABSTRACT: This paper presents a theoretical model of collusion and regulation in a wholesale electricity spot market. Given a demand for electricity, competing generators report their marginal costs. Then, only generators with the lowest marginal costs are selected to sell at a price equal to the marginal costs of the last generator selected to sell. The results show that under a fixed price level it is a weakly dominant strategy to truthfully report the marginal cost. Variable (or endogenous) prices create the possibility of profitable collusion among generators. With uncertainty in the marginal costs and risk neutrality, the results show that a necessary condition for collusion to be sustainable is that the marginal cost reported by the pivot (marginal generator) should be higher than the average of the true marginal costs of all the generators. The existence of collusion fines and audit probabilities were found to be effective in deterring collusion. It is also shown that more efficient generators have less incentive to collude.

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1. Introduction

Electricity is a widely consumed service, used as input for nearly all products in the economy and consumed also as a final good. Electricity is a critical input for many of the services we associate with modern life, from computers and televisions to cell phones and electric light. The electric power industry in the United States has been growing steadily over the last decades even at a higher pace than the Gross Domestic Product (GDP) and currently accounts from approximately 3.4 percent of the GDP. Moreover, electricity is a major manufacturing sector and accounts for about 35 percent of primary use of energy in the United States.

The generation of electricity has been widely used as the typical textbook example of 'natural' monopoly, where the government regulation was needed to achieve the efficient production levels. Important changes have been occurring in the industry worldwide in terms of the market structure in the generation, transmission and distribution of electricity. During the last two decades many countries reformed and liberalized their electricity sectors in the form of privatization, deregulation or both (see Bushnell and Wolfram, 2005). This process has meant less regulation of the sectors that are or can be made competitive like the generation sector, and more regulation on the non-competitive sectors like transmission and distribution. While transmission and distribution are still largely considered as natural monopolies, the generation has been slowly moving towards a more competitive environment, where specific forms of government regulation and the strategic interaction among generators have been gaining attention from researcher and policy makers. The most important feature in the most recent structural and regulatory reforms in the electricity sectors in the U.S. and around the world has been to separate the potentially competitive segment from the structural natural monopoly segments.

As a result of this liberalization and reforms processes, the wholesale electricity market in many countries operates now as a spot market with characteristics that resembles a second price sealed bid auction. However, these spot markets may not be truthfully revealing mechanisms as the theory of second price sealed bid auction predicts and generators may behave anti-competitively and collude to raise their prices. The rent-seeking behavior of the generators makes the market deviate from efficiency goals, increasing the need of more precise regulation. While most policy makers will agree that the market reforms should enhance consumer welfare, there is no consensus on which regulatory schemes are more likely to achieve the benefits of competition (see Steiner (2001)). In addition, as Fischer and Serra (2000) point out, a market approach in the generation sector with a larger number of generators even though should intuitively make it more competitive, it must take into account the possibility of strategic behavior among generating companies.

This chapter proposes a regulation model that predicts the strategic behavior of the generators under the possibility of over-reporting their true marginal costs to benefit from a higher price. It is shown that the generators may have incentives to collude to receive higher marginal costs markups. The chapter also obtains the necessary and sufficient conditions for collusion to be sustained in a one shot game. Among the policy implications it was found that increasing the fines for colluding generators or increasing the probability of punishing the colluders deters generators from jointly raising their marginal costs. Finally, more efficient generators have less incentive to collude.

The chapter is structured as follows. Part 2 summarizes the typical organization of the electric power and reviews the relater literature. In Part 3 presents and discusses the general model followed by Part 4 that analyzes the possibility of collusion among generators. Finally, Part 5 presents the conclusions.

2. The Organization of the Electric Power and Related Literature

As explained in Joskow (1997), the U.S. supply chain of electricity has four segments: generation, transmission, distribution and retailing, with distribution and retailing usually referred to as only distribution. The generation of electricity involves the use of falling water, internal combustion engines, steam turbines powered by the combustion of fossil fuels, nuclear fuels and various renewable fuels, wind turbines, and photovoltaic technologies. The transmission involves the high voltage transportation of electricity between the generating sites and the distribution centers. The distribution function involves the delivery of low voltage electricity to residents and businesses and relies on wires and transformers from the distribution centers to the consumers.

The main goal in the structural and regulatory reforms in the electricity in the U.S. and in other countries was to separate a previously vertically integrated utilities into different segments. The main separation was between the potentially more competitive generation segment and the rest of the segments, commonly considered natural monopolies. Steiner (2001) explains how some OECD countries also implemented new regulations to liberalize the industry, in particular and as in the U.S., focusing on the introduction of competition in the generation segment.

While separating the generating segment and increasing the number of competitors within this segment is a good approach to increase competition and approach efficiency price levels, the reforms still need to combine this enhanced competition with additional regulation to prevent collusion among competing generators. The model in this chapter seeks to address a specific form of regulation in this market.

On related papers that also look at regulation in a wholesale electricity spot marker, we have Green and Newbery (1992), who present a similar model for the British electricity spot market. In their model generators submit a supply schedule of prices and then receive a market-clearing price, which varies with demand. Consistent with our mode, their results show that in the resulting Nash equilibrium firms benefit from a high markup on marginal costs and there are large deadweight losses. Compared to Green and Newbery (1992), the model in this chapter additionally includes the role of audit probabilities and fines for misreporting marginal costs. Wolfram (1999) presents an empirical study of the market power in the British electricity spot market. Her results show that the estimated price markups are smaller than what most theoretical model would predict. She finds that generators respond to actions taken by the regulator, behavior captured by our model. In an empirical paper that can be used to motivate our model, Puller (2007) finds empirical evidence of collusion in the California electricity market in 2000, consistent with the higher prices and collusion modeled here. Newbery (1998) extends the British electricity spot market by including a contract market and contestable entry while van der Fehr and Harbord (1993) propose a model of seal-bid multiple-unit auction similar to the one presented in this chapter.[1]

3. The Model of Electricity Generation

This section presents a theoretical model of regulation and strategic interaction among electricity generators in a wholesale spot market. The biggest problem in the typical structure of the electricity industry is that the transmission company may behave as a monopsonist in its factor market and as a monopolist in its product market. Therefore the usual rule in the regulation of the industry is that the transmission company never owns the electricity. This means that the distribution companies buy directly from the generating companies in the wholesale electricity market. The wholesale market is formed by the supply and demand of electricity. The supply is

[1] For two good summaries of additional work on the reforms and structure of the electricity sector, see Joskow (1997) and Steiner (2001).

the summation of the reported minimum marginal costs of the generating companies and the demand is the summation of the individual demands of the distribution companies. The generators that end up selling electricity are the ones with the lowest reported marginal costs up until the demand of the distribution companies is met.

The price in the spot market is equal to the reported marginal cost of the last generator selected to sell electricity. Let this generator be the pivot generator. If a given generator reports a lower marginal cost than the pivot it will sell electricity, otherwise it will be left out. Notice that the reported marginal cost does not necessarily have to be equal to the true marginal costs. In addition, the price markup of each of the participating generators is the difference between the reported marginal costs of the pivot generator and their true marginal costs. This basic wholesale market scenario of price determination gives the generators the opportunity to collude, misreport their true marginal costs and jointly increase the price. Hence, higher efficiency levels in terms of lower prices can be achieved if regulation exists to eliminate or reduce marginal cost misreporting. The price determination process initially resembles a second price sealed bid auction. However, as just mentioned, the key difference is that there is the possibility that the generators collude and raise jointly their marginal costs to increase their markups. To avoid this behavior the regulator can carry out technical inspections to detect marginal cost misreporting and can charge a fine if a generator is found misreporting. This section of the chapter models the optimal behavior of each generator under this possibility.

Consider the existence of N generators participating in the wholesale electricity market. Each of these generators is denoted by $i = 1, 2, \dots N$. For a given day each generator has to submit a close envelope specifying the reported marginal cost at which this generator will make its capacity available for each of the next 24 hours. Therefore, for each generator and each hour period there will be a pair (DMC_i, V_i) where DMC_i refers to the reported or declared marginal cost and V_i is the capacity of generator i. Note that V_i is known by all the players and is obviously constant for a given generator during the whole day.[2] Because DMC_i is not necessarily the true marginal cost for generator i, we will demote the true marginal cost as just MC_i.[3]

Without loss of generality let $DMC_1 \leq DMC_2 \leq \cdots \leq DMC_N$. That is, we order the marginal cost declarations from the lowest to the highest. The summation of the individual

[2] Each generator may have more than one generating plant. In this case it is easy to extend the current model by making i denote each generating plant instead of the each generator.

[3] The possibility that generators can misreport their true marginal costs is mentioned in a number of articles, see for example Wolfram (1999).

demands of each of the distributors is equal to the aggregate demand and this one is denoted by X. This aggregate demand has to be covered by the generators that reported the lowest marginal costs. The price is set by the marginal cost of the last generator to enter the pool. This generator is called the pivot (p) or marginal generator with the declared marginal cost DMC_p. The selection of the pivot basically comes from the minimum p that satisfies:

$$\sum_{i=1}^{p} V_i \geq X. \tag{1}$$

For the sake of simplicity let's consider the case where the above inequality holds with equality. This means that the demand is satisfied exactly with an integer number of generator and none has to produce at partial capacity.

Auditing the generators to verify that they are reporting their true marginal costs is expensive and hence cannot be done the whole time and one every generator. To model random audits, there is a probability q that the regulator audits and punishes the generators when they are caught over-reporting their true marginal costs. This probability depends on the amount of marginal cost over-reported, $q_i = q_i(DMC_i - MC_i)$, and when they declare their true marginal costs it can be normalized to zero, $q_i(0) = 0$. When caught over-reporting, the generators are punished by having to pay a fine proportional to the sales value of over-reporting. Therefore, the amount of the fine is given by $sV_i(DMC_i - MC_i)$, where s is the fine rate, $0 < s < 1$, and $DMC_i - MC_i$ is the marginal cost over-reported.[4]

The generators are assumed to behave rationally and their behavior follows the Von Neumann-Morgenstern axioms under uncertainty. Each generator i chooses the declared marginal cost, DMC_i, that maximizes its expected profit given by:

$$E[\Pi_i] = (1 - q_i) \cdot \Pi\left[V_i\left(DMC_p - MC_i\right)\right] + q_i \cdot \Pi\left[V_i\left(DMC_p - MC_i\right) - sV_i(DMC_i - MC_i)\right]$$

$$\text{s.t.} \qquad DMC_i \geq MC_i. \tag{2}$$

[4] This model follows the economics of crime approach presented in Becker (1968), where misreporting is considered to be the crime.

Notice that DMC_p is not exogenous in the above equation and it actually depends on DMC_i as well as on the declared marginal costs of the other generators, DMC_{-i}. If this particular generator i ends up declaring a marginal cost higher than the pivot's marginal cost, it will be left out of the market and its expected profit will be zero because $V_i = 0$.

Equation 2 measures the profit above zero economic profits and the pivot's reported marginal cost is the price. The first term on the right hand side of the equation is the profit when not audited, with probability $1 - q_i$, and it is just the profit from the over-reported marginal cost times the generated quantity. The second term on the right hand side of the equation is the profit when audited, with probability q_i, and taking into account the fine from over-reporting.

Proposition 1. In the wholesale market, with an exogenous DMC_p, it is a weakly dominant strategy for each generator i to declare its true marginal cost MC_i.

Proof. Suppose $DMC_i > MC_i$. If $DMC_i > DMC_p > MC_i$, then the generator will be left out of the market without selling electricity because its declared marginal cost is higher than the declared marginal cost of the pivot. Hence, its profit will be equal to zero. If $DMC_i > MC_i > DMC_p$, once again the generator will be left out of the market with zero profits. If $DMC_p > DMC_i > MC_i$, the generator's expected profit will be positive and decreasing on the difference between DMC_i and MC_i, therefore when these two values are closer together the expected profit will be higher. The expected profit will be then maximized when $DMC_i = MC_i$. ■

What proposition 1 indicates is that when the generators cannot affect the price through DMC_p, the wholesale market will achieve its efficient outcome. All N generators will truthfully report their true marginal costs, the most efficient generators will sell electricity and the less efficient generators will be left out. Notice that this pricing mechanism works efficiently even with DMC_i being private information, the regulators and the distributors cannot observe it. The strong assumption for this result is the exogeneity of DMC_p. This exogeneity assumption means that generator i cannot affect DMC_p, which includes the possibility that when i is the pivot, increasing it's declared marginal cost will not affect DMC_p and it will just leave this generator without selling electricity. This assumption is not realistic as the generator who is the pivot will have the incentives to over-report its marginal cost to increase the price and benefit from a higher markup. The next section will endogenize DMC_p to analyze the incentives the pivot has to benefit from a higher price. In addition, even if the generator is not the pivot, a collusion agreement among the generators along with an endogenous DMC_p will provide the incentives for generators to over-report their true marginal costs.

4. The Model with Collusion

We not turn to the analysis of the model under the scenario of endogenous DMC_p and where the generators can collude to jointly increase their reporter marginal costs. To make the analysis tractable we simplify the model and assume that all the generators have the same capacity and we normalize this capacity to be equal to one, $V_i = V = 1$ for all i. This means that all units have the same size. The objective function becomes:

$$E[\Pi_i] = (1 - q_i) \cdot \Pi\left[DMC_p - MC_i\right] + q_i \cdot \Pi\left[\left(DMC_p - MC_i\right) - s(DMC_i - MC_i)\right]. \tag{3}$$

Notice that with this simplifying assumption is not restrictive as we can always go back to the original model by just changing the definition of i, from i being a given generator to i being each of the units of capacity of a given generator. Building on the model described above, consider the case where there are only three generators that have access to the same technology, hence they have the same cost structure. The marginal costs of each generator depend on various components, such as the fuel costs and the heat rate that is influenced by the atmospheric pressure and the temperature where the generator is located. This means that even though all generators share the same technology, each period resulting marginal costs have a random component that is unobserved by the regulator. To model this random component, let the marginal costs that each generator i has be of three different types: High (H), Medium (M), and Low (L), where by definition $MC_{i,H} > MC_{i,M} > MC_{i,L}$. The first subscript denotes the generator i and the second subscript denotes the type of marginal cost of the generator, H, M, or L. Whether each generator ends up being high, medium or low is not under the generators' control. Each type of marginal cost has a probability of $1/3$ of happening.

Consider the case where in each hourly period two out of the three generators end up producing. This means that demand is equal to two, $X = 2$, with two generators selling electricity and one generator left out of the production process. The expected profit that each generator i has to maximize is given by:

$$E[\Pi_i] = \frac{1}{3} \sum_{k=H,M,L} \{ (1 - q_{i,k}) \cdot \Pi[DMC_p - MC_{i,k}] + q_{i,k} \cdot \Pi[(DMC_p - MC_{i,k}) - s(DMC_{i,k} - MC_{i,k})] \} \tag{4}$$

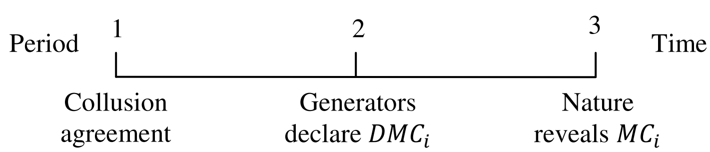
where $q_{i,k} = q_{i,k}(DMC_{i,k} - MC_{i,k})$, $i = 1, 2, 3$ and $k = H, M, L$. With exogenous DMC_p, and from Proposition 1, every generator will declare its true marginal costs, $DMC_i = MC_i$. When the generator i has medium marginal cost $MC_{i,M}$ it gets to be the pivot and has zero price markup, when it has high marginal cost $MC_{i,H}$ it ends up out of the market without producing electricity and when it has low marginal cost $MC_{i,L}$ it sells electricity with a positive markup. With this in mind and normalizing $\Pi(0) = 0$, Equation 4 becomes:

$$E[\Pi_i] = \frac{1}{3} \Pi[MC_{i,M} - MC_{i,L}]. \tag{5}$$

Equation 5 presents the expected profit when there is no collusion, generators report their true marginal costs and DMC_p is taken as exogenous. To analyze whether it is profitable for generators to engage in collusion and marginal cost misreporting, the profit shown in Equation 5 has to be compared with the profit level when generators collude and jointly increase their declarations to benefit from a higher price given by DMC_p.

Consider the collusion strategy where the three generators decide to jointly inflate their declarations. The collusion is done every day by dividing the 24 hours in three with each generator being out of the market eight times, being pivot eight times and being in the market eight times (hours). The time line for the collusion agreement, declaration and revelation of the true marginal costs is showed in Figure 1.

Figure 1. Time line



In period one the generators have to pact on the collusion agreement, that is which of the 24 hours of the day they will be playing as In, Out or Pivot. In the second period the generators send their closed envelopes and declare their marginal costs. Finally, in the last period of the day, nature reveals the true marginal costs. By the way the problem is set periods two and three can be switched with no additional effects on the model. After the collusion agreement is set, each generator maximizes the following expected utility:

$$E[\Pi_i] = \frac{1}{3} \sum_{i=pivot,In,Out} \left\{ \frac{1}{3} \sum_{k=H,M,L} \left[(1 - q_{i,k}) \cdot \Pi(DMC_p - MC_{i,k}) + q_{i,k} \cdot \Pi\left((DMC_p - MC_{i,k}) - s(DMC_{i,k} - MC_{i,k}) \right) \right] \right\} \tag{6}$$

When a generator has to act as a pivot, regardless of its true marginal cost, it declares $DMC_{pivot,k} = DMC_p$. When the generator has to act as In, it declares truthfully because there is no incentive to over-report. In addition, declaring the true MC_i minimizes the probability of being punished and the penalty if caught over-reporting. At last, when the generator has to act as Out, it just has to declare a marginal cost a little bit higher than the marginal cost of the pivot. To make this marginal cost minimize the probability of being punished and the fine if caught over-reporting, it has to be $DMC_{Out,k} = DMC_p + \delta$, where δ is an arbitrarily small positive number. Following this strategy will just make this generator obtain zero expected profit. With all these considerations, Equation 6 reduces to:

$$E[\Pi_i] = \frac{1}{9} \sum_{k=H,M,L} \left\{ (1 - q_{pivot,k}) \cdot \Pi\left[DMC_p - MC_{pivot,k}\right] + q_{pivot,k} \cdot \Pi[(1-s)(DMC_p - MC_{pivot,k})] \right\} + \frac{1}{9} \sum_{k=H,K,L} \Pi[DMC_p - MC_{In,k}] \tag{7}$$

Equation 7 shows the expected profit when generators do not collude. Assuming a linear profit function or risk neutrality if the profit function is taken as the firms' utility function and constant q if the firm is caught and punished over-reporting, we can derive the conditions under which generator i will find collusion profitable. To do this we compare the expected utility from collusion and from no collusion using Equations 5 and 7 to find that collusion is profitable when the following inequality is satisfied:

$$MC_{i,M} - MC_{i,L} < (2 - s \cdot q)\left[DMC_p - \frac{1}{3}\left(MC_{i,H} + MC_{i,M} + MC_{i,L}\right)\right]. \tag{8}$$

Equation 8 is the sufficient condition to have collusion in the spot market for a one shot game. The game needs to be played as a one shot because this condition relies on the additional assumption that the two generators collude in period 1 and do not deviate from the collusion agreement in period 2. The following propositions are obtained from Equation 8.

Proposition 2. Under risk neutrality, a necessary condition to achieve collusion is that the marginal cost declared by the pivot must be greater that the average marginal costs of all the generators.

Proof. The left hand side of Equation 8 is necessarily positive by construction. To have a positive number in the right hand side, the term in square brackets should be positive. ■

Proposition 3. Under risk neutrality, increasing the fine for colluding generators or increasing the punishment probability, both decrease the incentives to collude.

Proof. Increasing s or q, both reduce the right hand side of Equation 8. ■

Proposition 4. Under risk neutrality, the possibility of collusion is decreasing on the difference between the medium marginal cost and the low marginal cost.

Proof. When the difference between $MC_{i,M}$ and $MC_{i,L}$ is larger, it is less likely that the inequality in Equation 8 holds. ■

The policy implication from Proposition 3 is that the regulatory agency should increase the probability of auditing or increase the fine rate to deter collusion. While increasing the audit probability is more costly than increasing the fine rate, large fine rates may be difficult to enforce. These results are consistent with the findings in Becker (1968). Proposition 4 implies that in a setting with more efficient units with lower marginal costs and higher price markups collusion is less feasible. More efficient units are more reluctant to collude while less efficient units are more likely to aim at colluding.

5. Conclusions

This paper presents a theoretical regulation model motivated in the typical wholesale electricity spot market. The model is constructed on the possibility of having generators that misreport their true marginal costs in order to maximize their expected profits. The results show that it is a weakly dominant strategy for the generators to report their true marginal costs when the price in the wholesale market is given. Hence, there are no incentives to collude. When the price is endogenous and equal to the pivot's declared marginal cost, generators have incentives to collude. Collusion means that generators misreport and jointly increase their reported marginal costs to benefit from a higher price markup.

The model is also used to characterize a collusion strategy in which there is uncertainty in the reported marginal costs. Under linear profit functions and comparing the expected profit levels from collusion and no collusion, it was found that a necessary condition for collusion to be sustained is that the marginal cost reported by the pivot should be higher than the average of the true marginal costs of all the generators. Moreover, the regulatory agency can deter collusion by either increasing the probability of auditing the regulators or the fine rate if they are caught misreporting. Finally, the model also finds that the possibility of collusion is decreasing in the difference between the marginal cost of the pivot and the marginal cost of the selling generator, meaning that more efficient units that have higher price markups make collusion less feasible.

Further research based on this setting could be done when allowing the possibility of cheating on the collusion agreement. The natural strategy for the cheater will be to report the true marginal cost whenever this generator has to be left out of the market or behave as the pivot. This will make the cheater achieve a higher payoff for a single period. In a dynamic setting where this game is played many times, the collusion agreement could be reached as a Subgame Perfect Equilibrium for sufficiently patient players (by Folk Theorem). Further lines of research may also want to consider modeling the possibility of marginal cost over-reporting alone when the generator performs as the pivot. Finally, the results obtained in this paper can be tested to see if it is robust to generalizations that allow a larger number of generators and a larger number of marginal cost types.

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