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Electricity Industrial Organization: What About the Strategic Behavior of Hydro and Thermal Operators?

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ABSTRACT

In this paper, we develop a two-period model where we analyze and compare a hydro/thermal electrical system under different industrial organization: monopoly, Cournot competition and collusion; under storage constraint, water availability constraint and thermal turbine capacity constraint. First, we prove that the technological complementarity has an important role in satisfying electricity demand in the different industrial organizations. Second, we show by the analytical resolution, that intertemporal private monopoly water transfer from off-peak season to peak season is not as high as the same transfer under a public monopoly and therefore this increases the market price. Under Cournot competition, an increase in the peak season demand implies a water transfer strategy from off-peak to peak season. The results of collusion show that the electricity price is less dependent on the hydropower capacity.

Keywords: Electricity Market, Monopoly, Competition, Collusion, Hydro, Thermal
JEL Classifications: L20, Q40, Q25

1. INTRODUCTION

The market structure of the electricity sector has been characterized by natural monopolies. In the last decade, the market liberalization process suggests that the electricity production is done by private generators that use different technologies such as: wind, hydroelectric, solar, thermal, etc. The main goal of liberalization is to achieve more cost efficient production, lower electricity prices, better resources allocation and more supply security. A common feature of many electricity markets is the coexistence of hydro and thermal generation technologies. Genc and Thille (2008), Genc and Thille (2012), Dakhlaoui and Moreaux (2004), Crampes and Moreaux (2001) and Crampes and Moreaux (2010) studied competition in electricity markets with mixed hydroelectric and thermal generation. Ambec and Doucet (2003) compare the centralized and the decentralized industry of the hydraulic system under water turbine capacity constraint and water abundance constraint. They show that the exercise of market power can reduce the probability of achieving the deregulation goals. In this paper, we use Ambec and Doucet (2003) framework to develop a two-period model where we analyze and compare a hydro/thermal electrical system under different industrial organizations: monopoly, Cournot competition and collusion; under storage constraint, water availability constraint and thermal turbine capacity constraint.

Our main contribution consists of providing an analytical comparison of these different market situations with a focus on producers' strategical behaviors according to the market structure. First, we prove that the technological complementarity has an important role in the satisfaction of electricity demand in the different industrial organizations. Second, by the analytical resolution, we show that intertemporal private monopoly water transfer from off-peak season to peak season is not as high as the same transfer under a public monopoly and therefore this increases the market price. We compare Cournot competition and collusion equilibriums and we show how the strategical water storage is used, in a collusive agreement, to increase the market price.

The rest of the paper proceeds as follows. In Section 2, we present the model. Then, in Section 3, we deal with public monopoly and private monopoly. In Section 4, we analyze the production problem under Cournot competition and collusion of hydro and thermal operators. We conclude in Section 5.

2. THE MODEL

We consider a two-period model in order to analyze the production market of electricity with hydro (H) and thermal (T) plants. The inverse demand of electricity during period t for any quantity Q_t is: $P_t = a_t - b_t Q_t$, with $a_t > 0$, $b_t > 0$ and $t = 1,2$.[1] The hydroelectric firm uses natural inflows of water in order to produce Q_t^H units of electricity during the period t. It is assumed that 1 unit of water yields α units of electricity ($\alpha > 0$) and we denote by e_t is the exogenous volume of water supplied in the reservoir during period t. The total production of H during the two periods is:

$$Q_1^H + Q_2^H = \overline{Q}^H = \alpha(e_1 + e_2) \quad (1)$$

Water available during period 1 can be used to produce electricity during the first period or can be stored in the reservoir for use in the second period. Hence, the hydro-producer is able to produce at no cost during the first period any quantity Q_1^H such that:

$$Q_1^H \le \alpha e_1 \quad (2)$$

The volume of water stored during period 1 entirely used to produce electricity in the second period. This volume is bounded by the reservoir capacity, denoted $\bar{s}$. The water storage constraint is written as:

$$Q_1^H \ge \alpha(e_1 - \bar{s}) \quad (3)$$

A production plan is any vector, $Q^H = (Q_1^H, Q_2^H) \in \Re_+ \times \Re_+$, verifying the constraints. The firm T produces electricity using fossil fuel input. The production cost of Q_t^T units of electricity, denoted C_t, is assumed to be a quadratic cost; $C_t(Q_t^T) = \frac{1}{2} c_t (Q_t^T)^2$ with $c_t > 0$. During each period t, the T plant is subject to the following production capacity constraint:

$$Q_t^T \le \overline{Q}^T, \forall t = 1,2 \quad (4)$$

A production plan of T is any vector, $Q^T = (Q_1^T, Q_2^T) \in \Re_+ \times \Re_+$, verifying the capacity constraint.

3. MONOPOLISTIC STRUCTURE

3.1. Public Monopoly

The optimal production plan of the public monopoly is a solution of the following problem:

$$\begin{cases} \max\limits_{Q_1^H, \{Q_t^T\}_{t=1,2}} \int_0^{Q_1} P_1(x)dx - C_1(Q_1^T) + \beta \left[\int_0^{Q_2} P_2(x) - C_2(Q_2^T) \right] \\ s.t. \text{ (1), (2), (3) and (4).} \end{cases}$$

β represents the discount factor. We denote by $\overline{\lambda}^H$, $\underline{\lambda}^H$ and $\lambda_t^{T_H}$ the Lagrange multipliers associated respectively to the water availability constraint at the off-peak season, the storage constraint and the capacity constraint of the plant T. The first order conditions are:

$$P_1(Q_1) - \overline{\lambda}^H = \beta P_2(Q_2) - \underline{\lambda}^H \quad (5)$$

$$P_1(Q_1) - C_1'(Q_1^T) = \lambda_1^T \quad (6)$$

$$P_2(Q_2) - C_2'(Q_2^T) = \frac{\lambda_2^T}{\beta} \quad (7)$$

According to (5), monopoly equalizes the marginal benefit of water release in the off-peak season to the actualized marginal benefit of water storage in the peak season. According to (6) and (7), the monopoly equalizes the marginal benefit of thermal production at t to the marginal cost. Replacing (6) and (7) in (5) yields to:

$$C_1'(Q_1^T) + \lambda_1^T - \beta C_2'(Q_2^T) - \lambda_2^T = \overline{\lambda}^H - \underline{\lambda}^H \quad (8)$$

According to the optimality condition (8), the monopoly equalizes the cost difference between producing 1 unit of thermal electricity in the off-peak season and producing one in the peak season to the cost difference between using 1 unit of water in the production process in the off-peak season and storing this unit for the peak one.

3.1.1. If the maximal production capacity of T is reached during the peak season

In contrast with the peak season, during the off-peak one, the demand is assumed to be not high enough to reach the maximal capacity. In that case, $\lambda_1^T = 0$ and $\lambda_2^T > 0$. The condition (8) becomes as following:

$$C_1'(Q_1^T) - \beta C_2'(Q_2^T) - \lambda_2^T = \overline{\lambda}^H - \underline{\lambda}^H \quad (9)$$

The maximal capacity of the thermal plant is reached in the peak season. In order to satisfy the peak demand, the use of this plant in the off-peak season will intensify, as will the water storage. Consequently, as the left side of equation (8) is reduced by λ_1^T, the equilibrium can be re-established, with an increase of $\overline{\lambda}^H$, so more water is stored is stored because the marginal cost of the water's immediate exploitation increases, or with a decrease of $\underline{\lambda}^H$, so the marginal cost of water storage decreases.

3.1.2. Case of non-binding constraints

Proposition 1: The optimal mixed system operating and the equilibrium prices of the public monopoly case are given by:

- During the off-peak season: $Q_1^H = \frac{a_1 - \beta a_2}{b(1+\beta)} + \frac{\beta}{1+\beta}\overline{Q}^H$,

  $Q_1^T = \beta \frac{a_1 + a_2 - b\overline{Q}^H}{(b+c)(1+\beta)}$ and $P_1 = \frac{\beta c(a_1 + a_2 - b\overline{Q}^H)}{(b+c)(1+\beta)}$.
- During the peak season: $Q_2^H = \frac{\beta a_2 - a_1}{b(1+\beta)} - \frac{\overline{Q}^H}{1+\beta}$,

  $Q_2^T = \frac{a_1 + a_2 + b\overline{Q}^H}{(b+c)(1+\beta)}$ and

1 1 and 2 represent respectively the off-peak period and the peak season.

$$P_2 = a_2 - b\left(\frac{\beta a_2 - a_1 - b\overline{Q}^H}{b(1+\beta)} + \frac{(a_1+a_2)+b\overline{Q}^H}{(b+c)(1+\beta)}\right).$$

The optimal production quantities by the T plant depend on the water turbine capacity of the plant H, the demand characteristics and the production cost of the plant T. In fact, the presence of the plant H makes the thermal plant's problem a dynamic one. Consequently, any increase in H turbine capacity during the off-peak season, equal to $\Delta\overline{Q}^H$, reduces the plant T production during the same season by a quantity equal to $\frac{b}{(b+c)(1+\beta)}\Delta\overline{Q}^H$. A supplementary exploitation of the free technology (H) equal to $\frac{\beta}{1+\beta}\Delta\overline{Q}^H$, compensates for the decision to reduce the use of the expensive technology (T). The substitution of the expensive technology by the free one reduces the price by a quantity equal to $\frac{\beta bc}{(1+\beta)(b+c)}\Delta\overline{Q}^H$. Furthermore, to satisfy a supplementary demand during the peak season, the producer uses both technologies. The latter reduces his water use during the off-peak season by $\frac{\beta}{b(1+\beta)}\Delta a_2$ in order to transfer it to the next period and increases his plant T production by a quantity equal to $\frac{\beta}{(b+c)(1+\beta)}\Delta a_2$. We notice that, in order to satisfy a supplementary demand during the peak season, the producer increases his use of the thermal plant in different proportions among periods, $\Delta Q_1^{T_H} < \Delta Q_2^{T_H}$. Besides, the technological complementarity is crucial for the supply security.

3.2. Private Monopoly

The optimal production plan of the private monopoly, under non-binding constraints hypothesis, maximizes the following problem:

$$\max_{Q_1^H,\{Q_t^T\}_{t=1,2}} \; P_1.Q_1 - C_1(Q_1^T) + \beta\left[P_2.Q_2 - C_2(Q_2^T)\right]$$

Proposition 2: The optimal mixed system operating for the private monopoly case is given by:

- During the off-peak season: $Q_1^H = \frac{a_1-\beta a_2}{2b(1+\beta)} + \frac{\beta}{1+\beta}\overline{Q}^H$ and $Q_1^T = \beta\frac{(a_1+a_2)-2b\overline{Q}^H}{(1+\beta)(2b+c)}$.
- During the peak season: $Q_2^H = \frac{\beta a_2 - a_1}{2b(1+\beta)} + \frac{\overline{Q}^H}{1+\beta}$ and $Q_2^T = \frac{a_1+a_2-2b\overline{Q}^H}{(2b+c)(1+\beta)}$.

Any increase in the production capacity of H equal to $\Delta\overline{Q}^H$ increases his production during the off-peak and the peak season by respectively by, $\frac{\beta}{1+\beta}\Delta\overline{Q}^H$ and $\frac{1}{1+\beta}\Delta\overline{Q}^H$, which constitutes the same variations done by the public monopoly. On the other hand, with technological complementarity, the producer reduces his usage of T plant in the off-peak and the peak season by quantities respectively equal to $\frac{2\beta b}{(1+\beta)(2b+c)}\Delta\overline{Q}^H$ and $\frac{2b}{(1+\beta)(2b+c)}\Delta\overline{Q}^H$. We notice a disproportion, between the public monopoly and the private one, on the substitution of T by H during both seasons. In fact, the reduction levels of the thermal quantities are superior in the case of a private monopoly and the private monopoly tends to transfer less water than the public one. Furthermore, in order to satisfy a supplementary demand during the peak season, the private monopoly reduces his H production of the off-peak season by a quantity equal to $\frac{\beta}{2b(1+\beta)}\Delta a_2$, in order to store water and compensates, this additional water storage, by increasing the production of T by $\frac{\beta}{(1+\beta)(2b+c)}\Delta a_2$. To satisfy the additional peak season demand, the water transferred is entirely used as well as a supplementary production via the T plant equal to $\frac{\Delta a_2}{(1+\beta)(2b+c)}$ units. Moreover, we find that the water transfer under a private monopoly is lower than the one under the public monopoly. In addition, the private monopoly thermal production quantities in both periods are lower than the public monopoly one. This behavior guarantees higher gains for the private monopoly. Nonetheless, in both cases, the technological complementarity played an important role in the efficiency of the electricity supply security.

4. COMPETITION AND COLLUSION

We consider a hydroelectricity producer and a thermal electricity one operating both in a decentralized electricity industry. We analyze first, the case in which the two operators compete and second, the case of a potential collusion.

4.1. Cournot Competition

The Nash equilibrium strategies of H and T producers are respectively denoted by q^{H*} and q^{T*}. The hydropower optimal production plan $q^{H*} = (q_1^{H*}, q_2^{H*})$ maximizes the intertemporal profit under the constraints (1), (2) and (3), the problem is as follows:

$$\begin{cases} \max\limits_{q_1^H} P_1(q_1^H, q_1^T)q_1^H + \beta P_2(q_2^H, q_2^T).q_2^H \\ s.t.\ (1), (2) \text{ and } (3). \end{cases}$$

The first order conditions yield that the producer seeks to equalize marginal revenues to marginal costs:

$$P_1' q_1^H + P_1 - \beta(P_2' q_2^H + P_2) = \overline{\lambda}^H - \underline{\lambda}^H \qquad (10)$$

The T optimal production $q^{T*} = (q_1^{T*}, q_2^{T*})$ maximizes the intertemporal profit with respect to the capacity constraint:

$$\begin{cases} \max\limits_{q_1^T, q_2^T} P_1(q_1^H, q_1^T)q_1^T - C_1(q_1^T) + \beta\left[P_2(q_2^H, q_2^T).q_2^H - C_2(q_2^T)\right] \\ s.t.\ (4). \end{cases}$$

The first order conditions related respectively to the off-peak and the peak season are as follows:

$$P_1 + P_1' q_1^T - C_1'(q_1^T) = \lambda_1^T \qquad (11)$$

$$\beta(P_2 + P_2^{'} q_2^T - C_2^{'}(q_2^T)) = \lambda_2^T \quad (12)$$

4.1.1. If one of the H plant's constraints is bounded

We distinguish two different situations. We consider first, a water scarcity situation in which the producer uses the entire water inflow of the off-peak season to produce q_1^{H*}. The first order condition (10) is reduced to the following equality: $\pi_1^{H'} - \overline{\lambda}^H = \beta\pi_2^{H'}$ and H's production is $(\alpha e_1, \alpha e_2)$. We consider second, a water abundance situation. The H producer chooses to store water for a future use and the water storage reaches its maximal capacity, $\overline{s}$. The optimality condition (10) is reduced to: $\pi_1^{H'} = \beta\pi_2^{H'} - \underline{\lambda}^H$ and the intertemporal water transfer implies the following vector of optimal production levels: $(\alpha(e_1 - \overline{s}), \alpha(e_2 + \overline{s}))$.

4.1.2. Case of non-binding constraints

Proposition 3: The Cournot game equilibrium is given by the following optimal production quantities:

$$q_1^{H*} = \frac{(a_1 - \beta a_2)(b+c)}{b(1+\beta)(3b+2c)} + \frac{\beta \overline{q}^H}{(1+\beta)},$$

$$q_1^{T*} = \frac{a_1\left[b(2+3\beta) + c(1+2\beta)\right] + a_2\beta(b+c)}{(2b+c)(1+\beta)(3b+2c)} - \frac{\beta b \overline{q}^H}{(2b+c)(1+\beta)}$$

$$q_2^{H*} = \frac{(\beta a_2 - a_1)(b+c)}{b(1+\beta)(3b+2c)} + \frac{\overline{q}^H}{(1+\beta)} \text{ and}$$

$$q_2^{T*} = \frac{a_2\left[b(3+2\beta) + c(2+\beta)\right] + a_1(b+c)}{(2b+c)(1+\beta)(3b+2c)} - \frac{b\overline{q}^H}{(2b+c)(1+\beta)}.$$

We notice that, if the off-peak season demand is low enough, such that $a_1 < \beta a_2$, then the optimal strategy of H is to produce more in the peak season and the one of T is to produce more in the off-peak season. In fact, the intertemporal behavior of H allows him to store water and that T is obliged to satisfy the residual demand. Moreover, to face any increase in the peak season's demand equal to Δa_2 units, the hydroelectricity producer stores, during the off-peak season, a water quantity equal to $\frac{\beta(b+c)}{b(1+\beta)(3b+2c)}\Delta a_2$ and the thermal producer satisfies partially the off-peak residual demand by increasing his production with a quantity equal to $\frac{\beta(b+c)}{(2b+c)(1+\beta)(3b+2c)}\Delta a_2$. The water transferred is entirely used by H during the peak season and T production increases by a quantity equal to $\frac{b(3+2\beta)+c(2+\beta)}{(2b+c)(1+\beta)(3b+2c)}\Delta a_2$. We notice that, in order to satisfy the peak season additional demand, the additional units of thermal electricity are more important than the additional production made in the off-peak season with which the latter satisfies the residual demand. We can assess that technological heterogeneousness allows more supply security.

4.2. Collusion

We assume that both firms (H and T) produce quantities that maximize the joint profit. We denote by $\hat{q}^T = (\hat{q}_1^T, \hat{q}_2^T)$ and $\hat{q}^H = (\hat{q}_1^H, \hat{q}_2^H)$ the solutions of the following maximization problem:

$$\max_{q_1^H, \{q_t^T\}_{t=1,2}} \pi_1^H(P_1(q_1^H, q_1^T), q_1^H) + \beta\pi_2^H(P_2(q_2^H, q_2^T), q_2^H)$$

$$+\pi_1^T(P_1, q_1^T, C(q_1^T)) + \beta\pi_2^T(P_2, q_2^T, C(q_2^T))$$

Proposition 4: If competitors are indifferent between the two periods ($\beta = 0$), the solution of collusion problem is: $\hat{q}_1^H = \frac{a_1 - a_2}{4b} + \frac{\overline{q}^H}{2}$, $\hat{q}_1^T = \frac{a_1 + a_2}{2(2b+c)} - \frac{b}{2b+c}\overline{q}^H$, $\hat{q}_2^H = \frac{\overline{q}^H}{2} - \frac{a_1 - a_2}{4b}$ and $\hat{q}_2^T = \frac{a_1 + a_2}{2(2b+c)} - \frac{b}{2b+c}\overline{q}^H$. The collusive Prices are: $\hat{P}_1 = \frac{a_1(4b+3c) + ca_2 - 2bc\overline{q}^H}{4(2b+c)}$ and

$$\hat{P}_2 = \frac{a_2(4b+3c) + ca_1 - 2bc\overline{q}^H}{4(2b+c)}.$$

Let's note first that, the collusion is possible only if the maximum capacity of the plant H belongs to the interval $\left[\frac{a_2 - a_1}{2b}, \frac{a_2 + a_1}{2b}\right]$. Moreover, the hydroelectric firm produces more during the peak season, whereas, the thermal firm produces similar quantities during the two seasons, $\hat{q}_2^H > \hat{q}_1^H$ and $\hat{q}_1^T = \hat{q}_2^T$. If we compare with the competition strategies, the off–peak production of H is less important in a collusive situation. As a matter of fact, H transfers more water to be used in the peak season in which the price is higher. In a collusive agreement, strategical water storage is increased in order to achieve a higher peak season price. Furthermore, the maximal capacity of H affects negatively the price, then, the more predominant the hydro technology is, the less expensive electricity is. Moreover, an increase in the maximal capacity implies a more important decrease of the price in a competition situation. Thus, in collusion, the price is less dependent on the maximal capacity.

5. CONCLUSION

In this paper, we show that the technological complementarity has an important role in satisfying the electricity demand in the different industrial organizations. By the analytical resolution, we show that intertemporal private monopoly water transfer from off-peak to peak season is not as high as this same transfer under a public monopoly and therefore this increases the market price. Under Cournot competition, an increase in the peak season demand implies a water transfer from the off-peak season to the peak one, nevertheless, the intertemporal water transfer is more important under a collusion. The possibility of a collusive agreement depends on the availability of water resources and the demand parameters. We notice that, in contrast to the competition case, under the collusion one, the quantities of H are not dependent on T's costs. Thus, if a variation in the production cost of thermal energy has no effect on hydroelectric quantities, then and under these hypotheses, it is very likely that the competition is eased by a collusive agreement.

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