Risk Aversion, Environmental Regulation and Cournot Competition on Electricity Wholesale Market

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Résumé

This paper analyses the effect of green energy promotion policies in a decentralized power industry. We develop a Cournot duopolistic competition between risk-adverse operators each detaining polluting and clean technologies. We show that the subsidy-based policy for green energy allows the liberalization of the electricity industry to achieve the double objective of reducing pollution and electricity prices. However, these effects are mitigated as the green firm is more risk adverse. Taxation policy of dirty technology is more effective in reducing pollution but we show how it can weigh against reducing the price and the electricity supply. However, if the risk aversion of the dirty operator increases, the negative effect of the tax decreases.

Keywords : wholesale electricity market, Cournot competition, Green technology, Dirty technology, Environmental regulation.

JEL Classifications : L94, Q25.

1 Introduction

The main objectives of the introduction of competitive mechanisms on the wholesale electricity market are : economic efficiency in production, energy selling price reduction, resource allocation improvement, and electricity supply security. Following this liberalization, several issues were raised regarding market operation, management of electric generation facilities, market inefficiencies, saturation of transmission capacity, etc. Despite a deep concern for the environmental issues of energy market, few economic studies have investigated the impact of liberalization of electricity industry on environment. Bigano (2004) showed that deregulation increases pollution since it opens home markets to dirty technologies. Lise et al. (2006) showed that the reduction of market dominance of large electric power producers can be beneficial for both the consumer through lower prices and the environment quality through lower emissions. Note that all these works have analysed the problem in a deterministic universe. However, demand uncertainty and risk aversion pervade all electric power industries. Uncertainty has been integrated in models of Johnsen (2001), Mathiesen et al. (2003) and Genc and Thille (2007) who analysed the production problem in a deregulated hydraulics-dominated industry upon assuming the risk neutrality of electricity operators. The effects of uncertainty and risk aversion on allocating water resources following the strategic conduct of electric power operators on the wholesale electricity market have also been analyzed by Rangel (2008) and Abbasi et al. (2014).

Analyses of environmental policies effects on deregulated electric power industry remain insignificant. Bohringer (2006) showed that in the absence of environmental regulation, the production of renewable energy is not profitable but could increase at the expense of thermal energy due to the implementation of economic measures such as tax and subsidy. Brécard (2008), analysed the effects of an "ad valorem" tax on consumer behaviour and production through the development of a two-stepped game opposing two vertically differentiated firms. It shows that when the differentiation decreases following the deterioration of the highest quality, competition would be enhanced driving lower prices. Therefore, the environmental damage worsens when the inflicted pollution is higher.

All these works have analysed the problem within a deterministic framework while neglecting two important characteristics in the electric power industry namely demand uncertainty and risk aversion of electricity operators. Our article takes into account uncertainty and risk aversion in order to analyse the strategy-oriented conduct of electrical operators under environmental regulations. We develop a static Cournot competition involving a polluting firm and another featuring green technology. We present the model with and without using any environmental policy using first as research instruments, the grant plans for green technology, then taxation system of polluting technology. We examine how production decisions and their impact on the environment are different from those obtained in the absence of an environmental policy. By comparing analytical results we show that a subsidy-oriented policy endorsing green energy reduces both the sale price of electricity and pollution. However, these effects are mitigated when the Green firm is more risk averse. The Dirty-technology taxation policy reduces significantly the pollution but it can play against the expected results of the liberalization of the electricity industry in terms reduction of electricity prices. However, this can be partly remedied to if risk aversion of both firms increases.

The rest of the article is organized as follows. Section 2 presents the assumptions model and the characteristics of the two electric power plants on the market. Section 3 is devoted to the computation and analysis of equilibrium without environmental policy instruments. In Section 4, we analyse Nash equilibrium in the presence of environmental policy, including tax and subsidy.

2 Model

We consider a model of imperfect competition in the wholesale electricity market with two asymmetric competitors [1]. The first firm has a Dirty technology (D), while the second has a Green technology (G) [2]. It is assumed that the total output is transmitted to a distributor whose role is coordination between the various electric power operators to adjust supply to demand of high voltage. We assume that the two generation facilities are interconnected by a high-voltage line network presumed constraint-free on its transmission capacity. [3]

2.1 Demand

Since we neglect the charge loss during transmission of energy [4] and that electricity is not a storable good, then the quantity produced is totally consumed. The inverse demand function is assumed to be linear :

$$P(q) = \widetilde{a} - q \tag{1}$$

We denote q as the amount of energy consumed, P as the price on electricity wholesale market and $\widetilde{a}$ as a parameter that measures the market size. We assume that $\widetilde{a}$ is a continuous random normally distributed variable with an expectation $\overline{a}$ and variance σ^2. [5]

2.2 Production

The green technology firm, G, produces x_G quantity of clean energy by using as input a non-polluting natural resource, with a linear production cost function [6] :

$$C(x_G) = c_G.x_G \tag{2}$$

where c_G is a positive parameter representing the marginal cost [7].

1. We analyse the operating problem in electricity production industry with given heterogeneous facilities. We overlook the issues of investment in new electricity production facilities and depreciation of existing ones. Lise et Kruseman (2006) have analysed investment problem.

2. G can produce high-voltage electricity generated from wind, using hydraulic technology, wind turbine, hydrokinetic turbine, biomass technology, ect., while D has thermal power plant based on gas, combined cycle, coal, etc.

3. Joskow et Tirole (2000), Willems (2000) have analyzed the congestion problem of the electric network and the saturation of the transmission capacity.

4. Lise et al. (2006) considered the charge loss.

5. Genc et thille (2007) et Abbassi et al. have used the same specification of the electricity demand.

6. Several economists assume that the hydroelectricity production envolves constant returns. Genc and Thille (2007), Bushnell (2003), Moreaux and Crampes (2001) and Dakhlaoui and Moreaux (2007) assumed that the operating cost of hydraulic facilities equals zero.

7. The production by green power plants requires a constant marginal cost evaluated at $4,71$ *euro* for hydraulic

The polluting technology firm produces a quantity, x_D, of electricity using fossil fuels as input. The production process involves decreasing returns, the cost is hence represented by a quadratic production cost function [8] :

$$C(x_D) = \frac{1}{2}.c_D.x_D^2 \tag{3}$$

Where c_D is a strictly positive constant.

Since electricity is a non-storable and homogeneous good, the electricity production is written as the sum of outputs from the two power plants : $q = \sum_{i \in \{G,D\}} x_i$.

2.3 Producer's profits

The producer's profit function i is written as the difference between the gain from electricity sales and the cost of its production :

$$\pi^i = P(q)x_i - C_i(x_i) = (\tilde{a} - \sum_i x_i)x_i - C_i(x_i), \quad \forall i \in \{G, D\} \tag{4}$$

x_i is the amount of electricity produced by i, using the cost $C_i(x_i)$.

Each operator i maximizes the expected utility of his mean-variance profit model. The concept of expected utility, introduced by Neumann and Morgenstern in 1944, is an extension of the concept of utility function for decision under uncertainty. The expected utility of random profit of agent i, denoted $W(\pi^i)$, [9] is defined by :

$$W(\pi^i) = E(U(\pi^i)) = E(\pi^i) - \frac{A_i}{2}V(\pi^i), \quad \forall i \in \{G, D\} \tag{5}$$

Where the utility function $U(.)$ is continuous, strictly increasing and concave. The marginal utility is then decreasing, in other words, for a given increase in profit, usefulness is lower as earnings increase. $V(\pi^i)$ is the variance of the producer i's profit [10]. Hence, $A_i = -\frac{U''(E(\pi^i))}{U'E(\pi^i))}$ is the coefficient of absolute risk aversion of Arrow-Pratt. This positive parameter measures the intensity of risk aversion [11]. The right side of equation (5) can be treated as a risk premium that captures the weight that the decision maker attaches to risk. In fact, the firm yields a part of it's random profit in exchange of a sure one.

plants (See the final Rapport Wuppertal institut (2012) "Étude stratégique de mix énergétique pour la production électrique en Tunisie").

8. Approaching the maximal capacity, the production of extra units of electricity requires more than a proportional increase of production cost. The most part of economists that studied the wholesale electricity market assumed that thermal plants requires quadratic costs. See Borenstein (1998), Crampes and Moreaux (2001), Dakhlaoui and Moreaux (2007), De Villemeur and Vinella (2007).

9. The mean-variance criteria, introduced by Markowitz in 1952, tells that the risk to minimize is measured by the variance.

10. $V(\pi^i) = E\left[(\pi^i - E(\pi^i))^2\right]$, if profit variance increases then the profit π^i became more risky.

11. Mathematically, A_i measure the degree of concavity of the utility function. The more important it is, the more absolute risk aversion is strong.

Each producer decides the quantity of production that maximizes his expected utility [12]. Using equations (1) and (4), the optimisation problem of i is written as :

$$\max_{x_i} W(\pi^i) = (\bar{a} - \sum_{i \in \{G,D\}} x_i)x_i - C_i(x_i) - \frac{A_i}{2} x_i^2 \sigma^2 \tag{6}$$

The first order conditions associated with each optimization problem will release the reaction function of firm i relative to the amount offered by its competitor j. The resolution of the equations formed by the reaction functions, will determine the Cournot-Nash equilibrium on the electricity wholesale market.

In the following sections, we first analyse the Cournot-Nash equilibrium without environmental policy instruments, and then compare it to the equilibrium strategies in the presence of environmental regulation.

3 Cournot equilibrium without environmental policy instruments

In this section, we assume that firm D has no incentive to reduce its dirty production, and firm G receives no support from the State.

Using equations (6) and (3), the optimization program of the firm D is then written as follows :

$$\max_{\{x_D\}} W(\pi^D) = (\bar{a} - \sum_{i \in \{G,D\}} x_i)x_D - \frac{1}{2}.c_D.x_D^2 - \frac{A_D}{2} x_D^2 \sigma^2 \tag{7}$$

The first and second [13] order conditions are :

$$\frac{\partial W(\pi^D)}{\partial x_D} = 0 \Leftrightarrow \bar{a} - x_G - 2x_D - c_D.x_D - A_D x_D \sigma^2 = 0 \tag{8}$$

$$\frac{\partial^2 W(\pi^D)}{\partial x_D^2} = -2 - c_D - A_D \sigma^2 < 0 \tag{9}$$

Using equations (6) and (2), the optimization program of the firm G is then written as follows :

$$\max_{\{x_G\}} W(\pi^G) = (\bar{a} - \sum_{i \in \{G,D\}} x_i)x_G - c_G.x_G - \frac{A_G}{2} x_G^2 \sigma^2 \tag{10}$$

The first and second order conditions are :

$$\frac{\partial W(\pi G)}{\partial x_G} = 0 \Leftrightarrow \bar{a} - x_D - 2x_G - c_G - A_G x_G \sigma^2 = 0 \tag{11}$$

12. We assume that the production capacity is large enough and never runs out.
13. The profit is a concave function then a global maximum exists.

$$\frac{\partial^2 W(\pi G)}{\partial x_G^2} = -2 - A_G\sigma^2 < 0 \quad (12)$$

The first order conditions (FOC) defined by equations (8) and (11) leads to the reaction functions :

$$x_D = \frac{\bar{a} - x_G}{2 + c_D + A_D\sigma^2} \quad (13)$$

$$x_G = \frac{\bar{a} - c_G - x_D}{2 + A_G\sigma^2} \quad (14)$$

The reaction function $\{f_i(x_j)\}, i \neq j, \forall i \in \{G, D\}, \forall j \in \{G, D\}$ is the best response of the operator i, $\forall i \in \{G, D\}$, which is the optimal amount of electricity output of i in reaction to the strategy of it's competitor j.[14]

Solving the equations system (13) et (14) gives the production optimal levels (x_G^*, x_D^*) and the electricity price (P^*) at Cournot equilibrium.

Proposition 1 **:**

The equilibrium of Cournot game between electric power operators G and D on the wholesale electricity market is :

$$x_D^* = \frac{\bar{a}(1 + A_G\sigma^2) + c_G}{(2 + A_D\sigma^2 + c_D)(2 + A_G\sigma^2) - 1} \quad (15)$$

$$x_G^* = \frac{\bar{a}(1 + A_D\sigma^2 + c_D) - c_G(2 + A_D\sigma^2 + c_D)}{(2 + A_D\sigma^2 + c_D)(2 + A_G\sigma^2) - 1} \quad (16)$$

$$P^* = \frac{(\bar{a}(1 + A_G\sigma^2) + c_G)(1 + A_D\sigma^2 + c_D)}{(2 + A_D\sigma^2 + c_D)(2 + A_G\sigma^2) - 1} \quad (17)$$

This equilibrium exists if and only if $c_G \leq \eta.\bar{a}$, with $\eta = \frac{1 + A_D\sigma^2 + c_D}{2 + A_D\sigma^2 + c_D}$ and $0 < \eta < 1$■

According to Proposition 1, Cournot equilibrium exists if and only if the marginal cost of production for G technology does not exceed by a fraction η the maximum price that the high voltage consumer is willing to pay ($\bar{a}$). This fraction depends not only on the cost parameter of D technology but also on its level of risk aversion.

The total amount of electricity produced in the market $X^* = x_D^* + x_G^*$ is :

$$X^* = \frac{\bar{a}(2 + A_D\sigma^2 + A_G\sigma^2 + c_D) - c_G(1 + A_D\sigma^2 + c_D)}{(2 + A_D\sigma^2 + c_D)(2 + A_G\sigma^2) - 1} \quad (18)$$

We also note that the green production amount exceeds the dirty one if the following condition is satisfied[15] : $0 < c_G \leq \mu.\bar{a}$ with $\mu = \frac{A_D\sigma^2 - A_G\sigma^2 + c_D}{3 + A_D\sigma^2 + c_D}$ and $\mu > 0$. The mix-energy scheduling of

14. since $\frac{\partial f_i}{\partial x_j}$ is strictly inferior to zero, we can confirm that the two products are strategic substitutes.

15. $\mu = 1 - \frac{3 + A_G\sigma^2}{3 + A_D\sigma^2 + c_D}$ and $\eta = 1 - \frac{1}{2 + A_D\sigma^2 + c_D}$. We necessarily have $\eta > \mu$ to make sure that c_G belongs to the existence sample.

the electricity industry depends not only on the cost parameter of each technology but also on the absolute aversion rates of operators as well as the variance of the demand. All the possibilities are summarized in the following proposition.

Proposition 2 :

The mix-energy scheduling of the industry at the Cournot-Nash equilibrium is as following :

(i) - If $c_D < \sigma^2(A_G - A_D)$ then $x_D^* > x_G^*$.

(ii) - If $c_D > \sigma^2(A_G - A_D)$ Then $\begin{cases} x_G^* \geq x_D^* & \text{si} \quad c_G \in [0, \mu.\bar{a}] \\ x_G^* < x_D^* & \text{si} \quad c_G \in]\mu.\bar{a}, \eta.\bar{a}] \end{cases}$ ■

The D operator has a greater market share than his competitor if his cost parameter does not exceed the difference between the two levels of risk aversion multiplied by the volatility of demand. In other words, if condition (i) is satisfied, it can be deduced that the imperfect competition on the electricity wholesale market coupled with a risk aversion of electric power operators such as $(A_G > A_D)$ and a low D cost can promote the degradation of the environment due to the intensive use of polluting technology. However, according to (ii), imperfect competition on the electricity market is in favour of the use of Green technology if both the parameter cost of D technology is superior or equal to the difference in risk aversion rates of firms multiplied by the variability of demand and marginal cost of the use of the green plant is inferior or equal to $\mu.\bar{a}$. On the other hand, if the marginal cost of G is higher so the electric production of D technology exceeds that of green technology in the Nash equilibrium.

More generally, proposition 2 summarizes the conditions under which the functionality of the electric power industry coupled with the operators' display of risk aversion on the market may favour either a degradation of the environment due to the intensive recourse to polluting technology or an improvement in the quality of the environment following the use of green technology.

Graphically, the equilibrium in the absence of environmental regulation is shown in Figure 1 :

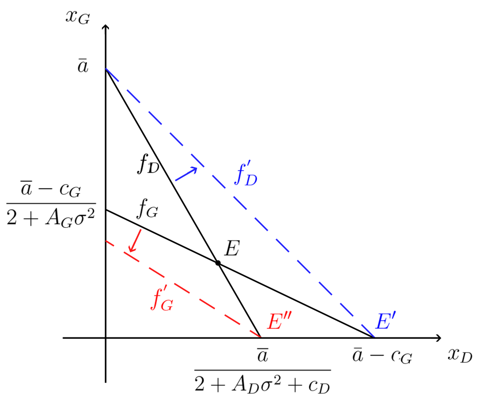

Figure 1 - Possible equilibriums without environmental policy

Figure 1 shows the two response functions f_D and f_G and the different possibilities of the equilibrium (E, E' et E'') according to the cost values and the level of absolute risk aversion of each power operator. Moreover, the Nash equilibrium may present as an internal solution or a corner solution.

Interior solution if $c_G < \eta.\bar{a}$

This equilibrium is graphically represented by the point E in Figure 1. The two rival firms produce strictly positive quantities.

Corner solutions : $c_G = \eta.\bar{a}$

According to the parameters of the models, two corner solutions are possible. These solutions are graphically represented by E' and E''. Although each corner solution is obtained by variation of different parameters, they both lead to the same form of the following equilibrium :

$$x_G^* = 0, x_D^* = \frac{\bar{a}}{2 + A_D\sigma^2 + c_D}, P^* = \frac{\bar{a}(1 + A_D\sigma^2 + c_D)}{2 + A_D\sigma^2 + c_D} \tag{19}$$

First, equilibrium E' is caused by a pivoting of f_D to the right. When A_D and/or c_D decrease, the expected utility of the profit of firm D increases and therefore the pivoting of its reaction function occurs on the right. Second, equilibrium E'' occurs when f_G moves to the left. Indeed, if c_G increases, the G firm sees its best response decreases thereby moving its reaction function leftward. The G firm cancels its production and D firm remains a monopoly. Furthermore, no conjecture of the market allows the firm G to regain monopoly. This proves that D is a basic energy to satisfy the demand.

We are now studying the effect of absolute risk aversion of each operational electrical operators on the market equilibrium. Figures 2 and 3 describe the impact of the change in absolute risk aversion levels, A_i, ($\forall i \in \{G, D\}$), on the production decision of the two firms.

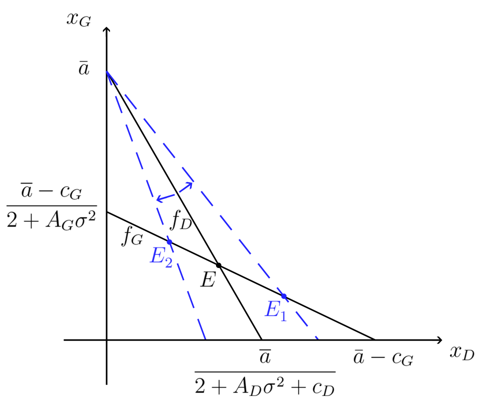

Figure 2 - Effect of A_D on the equilibrium.

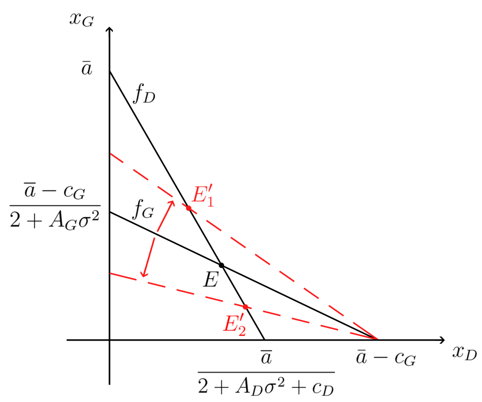

Figure 3 - Effect of A_G on the equilibrium.

According to Figure 2, the increase in the absolute risk aversion the firm D, A_D, involves pivoting of f_D to the left around $\bar{a}$ and the total effect deflects the equilibrium to E_2, then $x_D^{'}$ decreases and $x_G^{'}$ increases.

Graphically shown by the passage from E to E_2, the total effect can be decomposed into direct and strategic effects. When the polluting firm observes it's absolute risk aversion increasing, it decides to decrease its production to limit the decrease in the expected utility of its profit, thus constituting direct effect. The green firm anticipates the decline in production of its competitor following the increase of A_D and therefore chooses to strategically increase its quantity produced, thus constituting the strategic effect [16].

In addition, there is a particular equilibrium where it is not profitable to produce green energy, the corner solution E'. If the level of risk aversion of the operator D decreases to a minimum level $A_1^{min} = \frac{\bar{a} - (\bar{a} - c_G)(2 + c_D)}{\sigma^2(\bar{a} - c_G)}$, then the direct effect is an increase in the production level of firm D. Thus, firm G, having noticed the rapid decrease in the aversion risk level risk of its competitor, strategically decides not to produce anything because it anticipates that the entire market will be supplied by its competitor. Therefore, the duopoly problem turns into a monopoly problem.

$$x_G = 0, x_D = \bar{a} - c_G, P = c_G \tag{20}$$

The corner solution exists if and only if $\bar{a} \leq c_G(1 + \frac{1}{1 + c_D})$. Combining this condition with that of the positive quantities we obtain : $c_G(1 + \frac{1}{1 + c_D + A_D\sigma^2}) \leq \bar{a} \leq c_G(1 + \frac{1}{1 + c_D})$. The more c_G and/or A_D increases, the more restricted is the interval defining the size of the market. In other words, the more expensive the production of clean electricity is, the more $\bar{a}$ tends to c_G and so, according to equation (14) the more x_G tends to 0. The steeper the decrease of c_D and/or A_D is, the more amplified the interval that delimits $\bar{a}$ is, and the more lucrative the monopoly turns for D.

Figure 3 illustrates the effect of the variation in the absolute risk aversion of the second firm A_G. When A_G increases, f_G swings to the left around $\bar{a} - c_G$ deflecting the total effect of the equilibrium from E to $E_2^{'}$, then x_D increase, and x_G decreases. We can decompose the total effect into two effects. The first is direct effect, when the level of absolute risk aversion of firm G increases, the latter's decline it's production level. The second effect is the strategic effect, in fact, the first firm anticipates the decline in production of G company, following the increase of A_G and decides to strategically increase its production. Graphic analysis is validated by calculation, $\frac{\partial x_D}{\partial A_G} \geq 0$ if and

16. The economic intuition behind the strategic is : the decrease of x_D involves a rise in the market price and then the marginal incomes of G increases creating a disequilibrium $R_m^G \neq C_m^G$. G has to increase strategically her production to limitate the rise of the market price and to be in an equilibrium situation again.

only if $\frac{\bar{a}}{c_G} \geq \frac{2+c_D+A_D\sigma^2}{1+c_D+A_D\sigma^2}$ and we already know that this condition is validated because it is the same condition of the equilibrium existence.

Contrary to the extreme situation, described in the above equation (22), no monopoly is possible. Indeed, even if the risk aversion coefficient of G firm decreases to reach zero, the D company continues to produce and $x_D^* = \frac{c_G}{2(2+A_D\sigma^2+c_G)-1}$ and the firm G produce it's maximum amount : $x_G = \frac{\bar{a}(1+A_1\sigma^2+c_D)-c_G(2+A_1\sigma^2+c_G)}{2(2+A_1\sigma^2+c_D)-1}$.

We find that whatever the values of the Model parameters are, the equilibrium quantity of the polluting technology remains strictly positive. We conclude that Dirty energy is a basic energy while Green energy is a complementary one.

In the following sections, where the regulation come into play, we will figure out if clean energy can become a basic energy or not.

4 Cournot equilibrium with environmental policy

To encourage green production and discourage polluting production, the regulator can intervene with two different instruments of environmental policy : a unitary tax for polluting technology or a unitary subsidy on G production in green technology respectively denote by t and s the unitary tax on x_D production and unitary subsidy on x_G.

4.1 Equilibrium with green technology subsidy

We denote by s the level of unit subsidy granted to producers of G energy which reduce the production cost. The new cost function is then :

$$C(x_G) = c_G.x_G - s.x_G \tag{21}$$

From equations (6) and (21) we deduce the optimization program of G which is written as follows :

$$\max_{x_G} W(\pi^G) = (\bar{a} - \sum_{i\in\{G,D\}}^{2} x_i)x_G - c_G.x_G + s.x_G - \frac{A_G}{2}x_G^2\sigma^2 \tag{22}$$

The first and second order conditions are :

$$\frac{\partial W(\pi_2)}{\partial x_G} = 0 \Leftrightarrow \bar{a} - x_D - 2x_G - c_G - s - A_G x_G \sigma^2 = 0 \tag{23}$$

$$\frac{\partial^2 W(\pi_2)}{\partial x_G^2} = -2 - A_G\sigma^2 < 0 \tag{24}$$

From the FOC, specified by the equation (25), we deduce the reaction function of operator G :

$$x_G = f_2(x_D) : x_G = \frac{\bar{a} - (c_G - s) - x_D}{2 + A_G\sigma^2} \tag{25}$$

The subsidy does not affect the expected utility of firm D and it's reaction function is the same as in the case without subsidies. It is specified by the equation (15) : $x_D = f_D(x_G) : x_D = \dfrac{\bar{a} - x_G}{2 + c_D + A_D\sigma^2}$

By solving the reaction functions, the optimal electricity amounts of two firms as the Cournot equilibrium price P^s come to the next proposal.

Proposition 3 :

The Cournot game equilibrium between electrical operators in the presence of a subsidy is :

$x_D^s = \dfrac{\bar{a}(1 + A_G\sigma^2) + (c_G - s)}{(2 + A_D\sigma^2 + c_D)(2 + A_G\sigma^2) - 1}$

$x_G^s = \dfrac{\bar{a}(1 + A_D\sigma^2 + c_D) - (c_G - s)(2 + A_D\sigma^2 + c_D)}{(2 + A_D\sigma^2 + c_D)(2 + A_G\sigma^2) - 1}$

$P^s = \dfrac{(\bar{a}(1 + A_G\sigma^2) + (c_G - s))(1 + A_D\sigma^2 + c_D)}{(2 + A_D\sigma^2 + c_D)(2 + A_G\sigma^2) - 1}$

This equilibrium exists if and only if : $c_G \leq \eta.\bar{a} + s$ ■

This condition is less restrictive than the one imposed on the Green operator's marginal cost when there is no environmental regulations.

Note that the subsidy may never exceed the unit cost of Green production, indeed : $s \in]0, c_G]$. We also note that the G firm has a new unitary cost, diminished thanks to the subsidy, indeed : $c_G^{'} = c_G - s$.

Moreover, the optimal global production $X^* = x_D^* + x_G^*$ is :

$$X^s = \frac{\bar{a}(2 + A_D\sigma^2 + A_G\sigma^2 + c_D) - (c_G - s)(1 + A_D\sigma^2 + c_D)}{(2 + A_D\sigma^2 + c_D)(2 + A_G\sigma^2) - 1} \tag{26}$$

4.1.1 Effect of the subsidy on the Cournot equilibrium

To graphically evaluate the effect of the level of subsidy on equilibrium, we propose to draw a graph illustrating the reaction functions and the shift in equilibrium when the value of the subsidy varies :

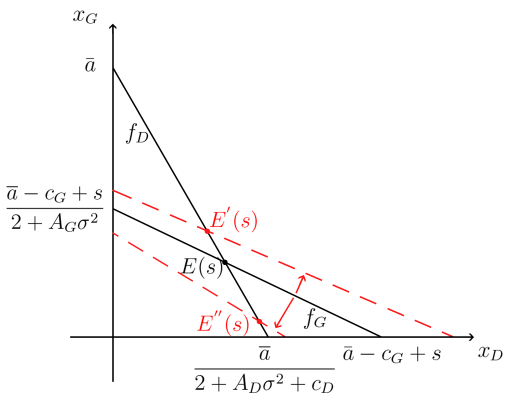

Figure 4 - Effect of s on equilibrium.

When the subsidy given to G increases, G's reaction function f_G shifts right shifting the equilibrium point $E(s)$ to the point $E^{'}(s)$. Thus, D production decreases and G production increases.

The global effect of the subsidy on the equilibrium is divided into strategic effect and direct effect. The increase of x_G^s is the direct effect of increasing the subsidy. Indeed, receiving more funding from the state, the marginal cost of G decrease so G decides to increase its production. Meanwhile, firm D expects that operator G will increase his production and decides strategically to reduce his own, which is the strategic effect.

Furthermore, no possible value of s could allow operator G to be in a monopoly position. Even if the subsidy is maximal (equal to the unitary production cost of G), operator D continues to produce without losses. When the subsidy is equal to zero, the situation is similar to the equilibrium without environmental regulation. Then, the Green firm can continue to produce. Following the non possible negativity of the Dirty electricity amount, this technology remains as an essential one.

Case 1 : The State subsidizes partially the Green technology ($s < c_G$)

Operator G has a new production cost equal to the old one deducted by the subsidy $c_G^{'} = c_G - s$. This cost tends toward zero as the grant approaches c_G. Comparing equilibrium with subsidy with the one without regulation, the subsidy has a negative effect on the polluting production amount, $x_D^s < x_D^*$, and a positive effect on the green one, $x_G^s > x_G^*$. Moreover, the direct effect is greater than the strategic one, indeed, the subsidy affects more G's decision than D's one : $\frac{\partial x_G^s}{\partial s} = \frac{2 + A_D\sigma^2 + c_D}{(2 + A_D\sigma^2 + c_D)(2 + A_G\sigma^2) - 1} > |\frac{\partial x_D^s}{\partial s}| = \frac{1}{(2 + A_D\sigma^2 + c_D)(2 + A_G\sigma^2) - 1}$.[17] In fact, operator D has no direct incentives to diminish his production, the decrease of D's production amount is due to competition mechanism. We note also that the amount of the quantities variations depends on both operators risk aversion and on the production cost parameter of the polluting technology.

17. $\frac{\partial x_G^s}{\partial s} = (2 + A_D\sigma^2 + c_D)|\frac{\partial x_D^s}{\partial s}|$.

Case 2 : The State subsidizes totally the Green technology ($s = c_G$)

This particular subsidy is perceived as a total refund of the production cost, then the production amount of the operator G is maximal as he produces for free. The total subsidization from the state is not only in favor of G, faced to this maximal increase of G's production, but operator D reduces significantly his own.

The equilibrium quantities according to this scenario are as follows [18] :

$$x_D^s = \frac{\bar{a}(1 + A_G\sigma^2)}{\alpha}, \; x_G^s = \frac{\bar{a}(1 + A_D\sigma^2 + c_D)}{\alpha} \tag{27}$$

With $\alpha = (2 + A_D\sigma^2 + c_D)(2 + A_G\sigma^2) - 1$

If the producers have the same risk aversion level, $A_D = A_G = A$, then the use of the clean technology is greater than the use of the polluting one, $x_G^s > x_D^s$ et $\Delta x^s = x_G^s - x_D^s = \dfrac{\bar{a}c_D}{\alpha}$. A total subsidization coupled with an homogeneous risk aversion leads to an energetic mix in favour of G technology.

4.1.2 Impact of absolute risk aversion and demand volatility on the subsidy efficiency

The positive effect of subsidy on the clean energy [19] is reduced by the absolute risk aversion of the two electric operators, $\dfrac{\partial^2 x_G^s}{\partial s \partial A_i} < 0, \; i \in \{G, D\}$. The subvention benefit of operator G is more diminished by his own risk aversion than the one of his rival, $|\dfrac{\partial^2 x_G^s}{\partial s \partial A_G}| > |\dfrac{\partial^2 x_G^s}{\partial s \partial A_D}|$ [20]. In other words, the presence of a subsidy enhances the clean production but this benefit is reduced by the risk perception level and also by the risk on it's own. Indeed, the demand volatility restrains G operator to make the most of that opportunity ($\dfrac{\partial^2 x_G^s}{\partial s \partial \sigma^2} < 0$). The behaviour of G is proportional to the risk parameters ; he chooses to not increase too much his production level in order to guard against the risks of low demand.

Concerning the polluting quantity, the disadvantage providing from the use of a subsidy, $\dfrac{\partial x_D^s}{\partial s} = \dfrac{-1}{(2 + A_D\sigma^2 + c_D)(2 + A_G\sigma^2) - 1} < 0$, decrease with the risk aversion of the two firms and with the demand volatility σ^2 ($\dfrac{\partial^2 x_D^s}{\partial s \partial A_i} > 0$ and $\dfrac{\partial^2 x_D^s}{\partial s \partial \sigma^2} > 0$). The strategic behaviour of D follows the market mechanism, as he already reduced his production quantity due to the subsidy, the increase of risk aversion can allow him to increase his production as he didn't reach yet his riskiest potential.

18. If $A_G - A_D < \dfrac{c_D}{\sigma^2}$ then $x_G^s > x_D^s$, (Same as in proposition 2).
19. $\dfrac{\partial x_G^s}{\partial s} = \dfrac{2 + A_D\sigma^2 + c_D}{(2 + A_D\sigma^2 + c_D)(2 + A_G\sigma^2) - 1} > 0$
20. $\dfrac{\partial^2 x_G^s}{\partial s \partial A_G} = \dfrac{-\sigma^2(2 + A_D\sigma^2 + c_D)^2}{((2 + A_D\sigma^2 + c_D)(2 + A_G\sigma^2) - 1)^2} < \dfrac{\partial^2 x_G^s}{\partial s \partial A_D} = \dfrac{-\sigma^2}{((2 + A_D\sigma^2 + c_D)(2 + A_G\sigma^2) - 1)^2}$

The presence of demand volatility and risk aversion reduces the efficiency of the subsidy to prevent the environmental pollution and to achieve an energetic mix in favour of a greater clean technology.

If, despite the uncertainty, the increase of G production is higher than the decrease of D production : $\Delta x_G > |\Delta x_D|$, then, the total amount of electricity produced is higher $X^s > X^*$. Therefore, the electricity price decrease and it's variation is : $\Delta P = P^s - P^* = -\frac{s(1+A_D\sigma^2+c_D)}{(2+A_D\sigma^2+c_D)(2+A_G\sigma^2)-1}$. Then, the subsidy provides a security in power supply and a higher competition that leads to a lower electricity price.

However, while this decrease in electricity price is reduced by both risk aversion of G and demand volatility ($\frac{\partial^2 P}{\partial s \partial A_D} < 0$ et $\frac{\partial^2 P}{\partial s \partial A_G} > 0$), if A_G is higher than a fraction of A_D, then absolute risk aversion of the polluting operator has a positive effect on the subsidy impact on the price [21]. The more D is risk averse (and/or the less uncertain is the demand) the more competitive is the price. [22].

To achieve an energetic mix in favour of clean technology, the minimal demand level requested is : $\bar{a}^{min} = (c_G - s)\frac{3+A_D\sigma^2+c_D}{A_D\sigma^2 - A_G\sigma^2 + c_D}$. The equilibrium with subsidy is more likely than the previous one (previous section) to lead to a Green predominant energetic mix.

4.2 Equilibrium with taxation of the polluting production

We suppose in this subsection that the regulatory imposes a unitary tax on the polluting production. The tax cost is added to the total cost function of operator D. The reaction function of G remains the same (equation (16)). The cost function of D is written as follows :

$$C(x_D) = \frac{1}{2}.c_D.x_D^2 + t.x_D \tag{28}$$

From equations (6) and (28) we deduce the optimisation program of D :

$$\max_{x_D} W(\pi^D) = (\bar{a} - \sum_{i\in\{G,D\}} x_i)x_D - \frac{1}{2}.c_D.x_D^2 - t.x_D - \frac{A_D}{2}x_D^2\sigma^2 \tag{29}$$

The first order condition is as follows :

$$\frac{\partial W(\pi^D)}{\partial x_D} = 0 \Leftrightarrow \bar{a} - x_G - 2x_D - c_D.x_D - t - A_D x_D \sigma^2 = 0 \tag{30}$$

We can deduce then the reaction function od D :

$$x_D = \frac{\bar{a} - t - x_G}{2 + c_D + A_D\sigma^2} \tag{31}$$

21. If $A_G > \frac{A_D}{(2+A_D\sigma^2+c_D)((1+A_D\sigma^2+c_D)}$ then $\frac{\partial^2 P}{\partial s \partial \sigma^2} > 0$.
22. The effect of A_G on the price variation is higher than the one of A_D.

Solving reaction functions (14) and (32), we identify the optimal production quantities of the two competitors and the market price. The Cournot-Nash equilibrium is presented on the following proposal.

Proposal 4 :

Cournot equilibrium of the game between the two electricity producers is presented as follows :

$$x_D^t = \frac{\bar{a}(1+A_G\sigma^2)+c_G-t(2+A_G\sigma^2)}{(2+A_D\sigma^2+c_D)(2+A_G\sigma^2)-1}$$

$$x_G^t = \frac{\bar{a}(1+A_D\sigma^2+c_D)-c_G(2+A_D\sigma^2+c_D)+t}{(2+A_D\sigma^2+c_D)(2+A_G\sigma^2)-1}$$

$$P^t = \frac{(\bar{a}(1+A_G\sigma^2)+c_G)(1+A_D\sigma^2+c_D)+t(1+A_G\sigma^2)}{(2+A_D\sigma^2+c_D)(2+A_G\sigma^2)-1}$$

The existence of this Nash equilibrium is subjected to the folling constraint : $t \in \left]0, \frac{\bar{a}(1+A_G\sigma^2)+c_G}{2+A_G\sigma^2}\right]$ et $c_G \leq \eta.\bar{a}$ ■

The optimal total production $X^t = x_D^t + x_G^t$ is :

$$X^t = \frac{\bar{a}(2+A_D\sigma^2+A_G\sigma^2+c_D)-c_G(1+A_D\sigma^2+c_D)-t(1+A_G\sigma^2)}{(2+A_D\sigma^2+c_D)(2+A_G\sigma^2)-1} \quad (32)$$

4.2.1 Effect of the tax on the equilibrium

In order to graphically analyse the effect of the tax variation on the equilibrium we use the following figure :

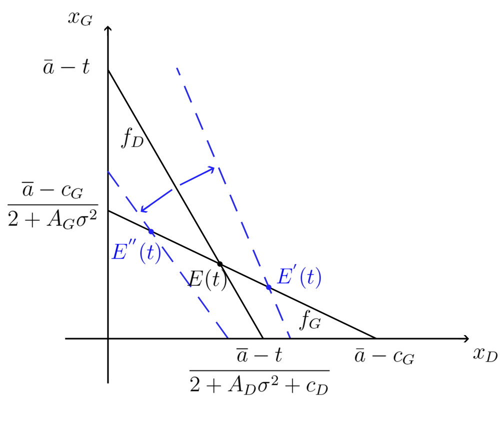

Figure 5 - Effect of t on the equilibrium.

Case 1 : Case of a moderated taxation of the polluting technology ($t < \frac{\bar{a}(1+A_G\sigma^2)+c_G}{2+A_G\sigma^2}$)

Let $E(t)$ be the initial equilibrium point. The total effect that derives equilibrium to point $E''(t)$ can be decomposed into direct effect and strategic effect. An increase of the tax level shifts f_D to the left, then, the polluting production decreases due to the increase of D's cost caused by the tax : it's the direct effect. Operator G reacts to the deviation of his rival and chooses to rise strategically his own production.

The tax reduces significantly the polluting production of D and increase slightly the clean production : $\frac{\partial x_G^t}{\partial t} = \frac{1}{(2+A_D\sigma^2+c_D)(2+A_G\sigma^2)-1} < |\frac{\partial x_D^t}{\partial t}| = \frac{2+A_G\sigma^2}{(2+A_D\sigma^2+c_D)(2+A_G\sigma^2)-1}$. Thus, the total amount of electricity produced decreases compared to the unregulated equilibrium, $\Delta X = X^t - X^* = \frac{-t(1+A_G\sigma^2)}{(2+A_D\sigma^2+c_D)(2+A_G\sigma^2)-1} < 0$. The taxation instrument achieve the environmental regulation goal, the pollution is lowest and the clean production is consequently promoted. However, this achievement is reached at the expense of a competitive price ($P^t > P^*$) and the power supply security.

Case 2 : Prohibitive taxation of the polluting technology ($t = \frac{\bar{a}(1+A_G\sigma^2)+c_G}{2+A_G\sigma^2}$)

The prohibitive tax allows operator G to oust completely his rival D from the wholesale electricity production market and to be in a monopolist situation. This particular tax satisfies entirely the aim of the regulation policy, no pollution at all is induced by the production process.

$$x_D^t = 0, x_G^t = \bar{a} - t = \frac{\bar{a} - c_G^t}{2+A_G\sigma^2}, P^t = t. \quad (33)$$

Although, the fact that only one firm satisfies the market supply leads to a failure of a liberalization initiative, that aims to enhance competitiveness in order to lower electricity price and to diversify production sources and technologies in order to secure power supply. The regulator needs to find the right balance between an ideal environmental quality and allowing coexistence and competitiveness between two diversified technologies.

4.2.2 Impact of absolute risk aversion and demand volatility on the taxe performance

The decrease of the polluting energy production under a taxation policy is even less high when D's risk aversion is important. Note that $\frac{\partial^2 x_D^t}{\partial t \partial A_D} > 0$, in other words, the more D is risk averse the less taxation policy is efficient to reduce polluting production. The result is the same concerning A_G, even if it's effect is less important than A_G's one, $\frac{\partial^2 x_D^t}{\partial t \partial A_G} > 0$ et $\frac{\partial^2 x_D^t}{\partial t \partial A_D} > \frac{\partial^2 x_D^t}{\partial t \partial A_G}$. Taking into account the risk aversion of the electricity operators shows that their perception of concrete risk and that the risk on itself (demand volatility) reduces the efficiency of a taxation policy ($\frac{\partial^2 x_D^t}{\partial t \partial \sigma^2} > 0$). Operator D is subject to a significant increase of his cost function due to taxation. When his risk aversion is important, he decreases his production quantity and this decrease in electricity supply is substituted in part by the clean technology. But, the more his own risk is higher, the less he decreases his production due to the behaviour of his rival G that can not strategically higher indefinitely and uniformly his input to fulfil the decrease in total supply. The fundamentals of game theory imposes to each player, to D in this case, to find the optimal balance between his own constraints (taxation and higher risk aversion) and the rival strategy based on his expected utility (G's expected utility in this case).

When G is more risk averse, it decides rationally to produce less. His rival D increases his production quantity, despite the fact that he is under a taxation policy, to substitute the loss in total energy supply. Then, under the market mechanisms, the efficiency of the taxation is less important when both players are more risk averse.

Taxation is perceived as an additional cost due to the pollution generated by the Dirty technology, thus, the equilibrium price under taxation is significantly higher than the unregulated one and the one under subsidy policy. the latest can be written as follows :

$$P^t = P^* + \vartheta.t \quad \text{avec} \quad \vartheta = \frac{t(1 + A_2\sigma^2)}{(2 + A_D\sigma^2 + c_D)(2 + A_G\sigma^2) - 1} \quad \text{et} \quad \vartheta < 0.5$$

The improvement of environmental quality is obtained at the expense of the competitiveness of the electricity price, the market supply security and the consumer welfare. Indeed, a part of the tax is directly transferred to the power price ; the consumers support a part of the policy expenses.

The more D is risk averse, the less the tax part supported by the consumers is important. Unlike the previous result, the more G is risk averse, the more the consumers tax part is low, $\frac{\partial^2 P^t}{\partial t \partial A_G} > 0$ et $\frac{\partial^2 P^t}{\partial t \partial A_D} < 0$.

Thus, we conclude that the subsidy policy is efficient in achieving goals of both the liberalization of wholesale electricity market and the environmental policy and leads to a diversified energy mix, $P^s < P^* < P^t$. Taxation significantly improves environmental quality but at the expense of competitiveness of the price and supply security. This disadvantage is however softened by the risk aversion. In addition, taxation policy can lead to a monopoly situation which cancels the diversification of the energetic mix.

5 Conclusion

This paper analyses the effects of environmental regulation on the electricity production in a heterogeneous system when both operators are risk averse. The existing literature has neglected important characteristics in the wholesale electricity industry such as demand uncertainty and risk aversion. An environmental policy in favour of Green technologies can, under some hypothesis, be efficient in improving the environmental quality and at the same time harmonious with the liberalization process. A regulated market can also harm the liberalization expectations.

This paper shows that the liberalization of the wholesale production industry coupled with a subsidy policy reduces both the energy price and the polluting energy quantity. But, these results are diminished by risky parameters. The presence of demand volatility and risk aversion reduce the efficiency of the subsidy to prevent the environmental pollution and to achieve an energetic mix in favour of a greater clean technology. Taxation is significantly improves environmental quality but at the expense of competitiveness of the price and supply security, this disadvantage is however softened by the risk aversion. Taxation policy can lead to a monopoly situation which cancels the diversification of the energetic mix.

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