Dynamic Behaviour of Hydro/Thermal Electrical Operators Under an Environmental Policy Targeting to Preserve Ecosystems Integrity and Air Quality

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Abstract

In this paper, we analyse the effect of an environmental policy that targets to enhance ecosystems integrity as well as air quality in the wholesale electricity market. We developed a dynamic Cournot game between a hydro and a thermal risk adverse electricity producers under demand uncertainty. We demonstrate that while improving air quality necessarily raises the market price, enhancing ecosystems integrity can, under water abundance hypothesis, reduce it. Moreover, in order to establish a statement about the environmental policy efficiency, we examine interactions between both environmental measures and their potential side effects. We show that prioritizing natural flow regime minimises necessarily the taxation efficiency on lowering air pollution and emphasizes the price rise due to the taxation. Nevertheless, the effect of the taxation policy on the efficiency of the ecosystems integrity policy depends on the hydro producer's ability to substitute thermal units. In order to establish a precise environmental statement, the regulation authority needs to compare, using appropriate criteria, the importance of an avoided unit of surrounding ecosystem alteration to an avoided unit of air polluting production, in the whole ecosystem functioning.

Keywords: Electricity generation; Environmental policy; Dynamic modelling; Imperfect competition; Ecosystems integrity; Air quality.

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1 Introduction

Electricity generation from renewable resources, including water, represents an important alternative to green gas emissions. Nevertheless, there is consensus among natural scientists on the negative impacts of hydropower on the environment. Research conducted for decades, has identified important correlations between hydropower operation and ecosystems quality. By the use of reservoirs to store water, hydropower producers modify the occurrence timing, the frequency, the intensity and the volume of natural flows, which impact surrounding habitat and biodiversity (Dresti *et al.*, 2015; Richter and Thomas, 2007, and Zahary and Ostrovsky, 2017). Moreover, ecosystems hardly adapt to significant and sudden water level fluctuations caused by management strategies of reservoirs in which water releases may be much higher or well below naturals levels (Choquette *et al.*, 2010; Richter and Thomas 2007; Cushman, 1985, and Moreira *et al.* 2018).[1] The very existence of reservoirs implies that the self-regulation of natural systems are inevitably altered and can never be reinstated (Moss 2008). Furthermore, as ecosystems viability is highly dependent on the natural dynamic character (Poff *et al.*, 1997), partial restoration of natural flow regimes have significant ecological benefits (Postel and Richter, 2012). Richter and Thomas (2007), highlight that prioritizing the characteristics of natural flow regimes, through ecological flow assessment, is necessary to achieve ecological benefits. In fact, the most suggested approach to mitigate alteration of natural ecosystems is a regulation measure that imposes a minimal ecological flow that producers have to guarantee (Dresti et al., 2015, and Pérez-Diaz et al., 2012). Truffer (2010) described this minimal ecological flow as sub-optimal on the grounds of the social dilemma provoked by hydropower.[2] The author suggests that the knowledge produced regarding the environmental impacts of hydropower has neglected important characteristics which are the political and social aspects. In addition, Moss (2008) suggests the establishment of mechanisms to minimize the consequences instead of continuously responding to a fluctuating demand. As a matter of fact, the optimal levels of reservoirs, as determined by existing management strategies, are not necessarily the optimal levels requested to protect surrounding ecosystems

1. Cushman (1985) and Freeman *et al.* (2001) studied the potential impacts of altered flow regimes, provoked by hydropower operation, on aquatic systems below dams and they both conclude that flow stability during appropriate season is essential for riverine organisms integrity. According to Cushman (1985), most species are not adapted to the unnatural water fluctuation patterns which causes several changes in stream habitat, reduce the abundance, the diversity and productivity of riverine organisms and finally results in an increasing mortality.

2. The author chronicles the political history of hydropower in Switzerland. In the early 1980s, environmental movements against hydropower attracted public attention on the negative impacts of hydropower on ecosystems and thus, at the end of the 1980s policy makers established minimum flow requirements.

(Choquette *et al.*, 2006). Indeed, the optimal reservoirs management strategies are those that maximize the benefits and ecological characteristics are conventionally added only as constraints. Jager and Smith (2008) suggest, in this regard, that reservoir management strategies should maximize simultaneously economical benefits and ecological ones. In addition, Bratich *et al.* (2004) consider that environmental and economic aspects should have the same importance while making decisions. Moreover, Crampes and Moreaux (2001) mentioned that the value of water should include, in addition to its value on the electricity generation, its value on other uses, such as agriculture.

To respond to the biodiversity degradation, we will refer to the ecological compensation principle [3]. The ecological compensation, a relatively new instrument, consists of a positive measure to correct, balance or atone the loss of environmental resources (Cowell 2000). In that regard, in Switzerland, the hydro producer has to invest a fixed payment per a unit of electricity sold and these eco-investments are intended to protect, restore or upgrade the surrounding ecosystems (Bratich *et al.* (2004)). Nevertheless, Rayamajhee and Joshi (2018) criticize the lack of specificity of existent compensatory measures [4] that aim to mitigate externalities provoked by the construction and the operation of a dam. They argue that most of those measures are not designed on the basis of a specific environmental externality and thus the resulting effect of such an ambiguous measure is either undercompensation or overcompensation for the damage. [5] Furthermore, an efficient compensation policy should first of all, reflect correctly the environmental damage by using an appropriate measure and, secondly, consider the specificities of the damages, their causes and their evolution over time. In that regard, biodiversity changes may have pervasive effects on earth system functioning and thus the consequences of biodiversity loss are non linear over time (Rockstrom *et al.*, 2009). Consequently, we will model an environmental cost, for the hydro producer to pay, on the basis of the ecosystems alteration caused by water level fluctuations. This environmental instrument aims to prioritize the characteristics of natural flow regime by minimising the gap between inflows and outflows.

Furthermore, several natural scientists consider that water level fluctuations, that are often sudden and significant, are exclusively due to the necessity of satisfying different demand patterns. First of all and in order to take into consideration this important aspect, which is demand fluctuations, we formalise the electricity demand as a parameter that varies with time. On another side, the information about

3. An economic actor who will destroy a valuable habitat, may do so only after paying a cost to the regulatory authority and this cost will be dedicated to restoring habitat of equivalent ecological value.

4. Called sharing-benefits.

5. The authors designed an endogenous mitigation fund, as a cost for the producer to pay, that accounts for negative effect of hydropower on agriculture.

the demand level is crucial for producers since electricity is a non storable good and producers have an immediate necessity to align, in real time, supply with demand. Consequently, we will consider in our model this crucial aspect which is the demand uncertainty.[6] In addition, we assume that producers are not risk neutral and that they are precisely risk adverse when they are facing uncertainty[7]. The idea of dropping the risk neutrality hypothesis is illustrated in Severin Borenstein's (2016) critical thinking: "So what can IO economists do to increase the field's R-squared? I think the big gains in the next decade will come much more from broadening than from deepening: from combining an IO approach with thinking about firm behaviour that is outside the narrow IO box". Secondly, we consider that water level fluctuations are not only due to demand patterns but also, to the optimal dynamic management strategies that guarantee the highest gain possible. In fact, the possibility to realise intertemporal water transfer implies opportunity costs and consequently dynamic management strategies. In that regard, Genc and Thille (2017), Rangel (2008) and Førsund (2015) mention the reallocation of water resources between periods as a strategy for hydro producers to exercise market power, the latter may indeed benefit from withholding water in periods with low prices in order to have more available for use in periods with high prices. Consequently, we consider that water level fluctuations can be reduced.

However, imposing an environmental cost to the hydro producer will inevitably have consequences on thermal production and may indirectly decrease the air quality. Thus, we will analyse a market in which the regulator imposes an environmental cost to the hydro producer and a taxation to the thermal one. In that regard, it is necessary to evaluate an environmental policy as a whole set in order to establish an optimal combination that insures conjointly biodiversity integrity and air quality.

We develop a dynamic Cournot game between a hydro and a thermal risk adverse producers under demand uncertainty hypothesis in the presence of environmental instruments. We will, first, analyse the competition and the strategic behaviours of those asymmetric players, that produce a homogeneous product, under environmental policies and demand uncertainty. Second, we will evaluate the efficiency of environmental instruments to lower degradations. Finally, we examine whether or not the expected liberalisation objectives are maintained in the presence of environmental instruments.

To the best of our knowledge, analytical works that examined dynamic imperfect competition on

6. Genc and Thille (2017), analysed a dynamic game with an infinite time horizon between a hydro generator and a thermal generator, they assumed that the demand intercept is an i.i.d. random variable.

7. Philpott et al. (2016) studied the market inefficiency caused by inflows uncertainty when electricity producers are price takers and risk adverse. They focused on a risk measure (to minimize) consisting of a combination between disbenefit expectation and average value at risk.

electricity markets under demand uncertainty hypothesis did not consider producers' risk aversion and/or an environmental instrument to protect ecosystems integrity.

The rest of the paper is organized as follows. In the next section we present the dynamic model hypothesis. The third section is dedicated to the analytic resolution of Cournot-Nash equilibrium in the presence of an environmental cost and the analysis of the players behaviours. In the fourth section we introduce a taxation policy, we analyse the equilibrium, the players behaviour, the environmental policies efficiency as well as the interactions between environmental instruments and their potential side effects. We end by concluding the paper.

2 Model

We consider a dynamic model of imperfect competition in the wholesale electricity market where two asymmetric producers are competing under a multi-period Cournot duopoly assumption.[8] Firm T produces high voltage electricity using thermal technology and firm H produces high voltage electricity using a hydraulic one. In this multi-period game, time is divided into an infinity of periods indexed by : $t = 0, 1, 2, etc.$ In each period t, each producer decides the optimal quantity of electricity to produce.

2.1 Demand

The inverse demand is assumed to be a linear function:

$$P_t = \tilde{a}_t - bQ_t, \tag{1}$$

Where P_t represents the electricity price, Q_t represents the electricity production quantity[9], $b \in]0, 1]$ is a constant, and $\tilde{a}_t$ is random normally distributed variable[10] (with an expectation equal to a_t and a variance equal to σ^2)[11] that measures the market size at time t.[12]

8. We analyse the operating problem in electricity production industry with given heterogeneous facilities. We neglect investment and depreciation dimensions.

9. Supposed to be totally consumed.

10. Uncertainty in demand is caused by unpredictable variations of economic activity.

11. We assume that demand variations are mainly structural (affecting only the central tendency) and that there is no significant reason for the volatility to change across periods.

12. Genc and Thille (2017), have modelled the demand uncertainty with the same specifications.

2.2 Electricity production

We define by q_t^T the electricity production of T at time t and by q_t^H the electricity production of H at time t. As electricity is a homogeneous good, then the total production of the industry is: $Q_t = q_t^T + q_t^H$.

2.2.1 The hydro producer

The hydropower player produces energy using water stored in a dam. [13]. The reservoir-dam is recharged in each period t by inflows of water denoted f_t. The evolution of available water in the reservoir is represented by the following recurrent equation:

$$S_{t+1} = S_t - q_t^H + f_t, \tag{2}$$

where S_t represents the water stock in the reservoir at time t and observed in the beginning of the period t. Moreover, H has to pay an environmental cost to minimize water level fluctuations. The regulator imposes a penalty on the difference between the current stock of water and next period's one. The environmental cost is specified as:

$$C_t^H(S_{t+1}) = \frac{\gamma}{2}(S_t - S_{t+1})^2, \tag{3}$$

where γ represents the environmental cost parameter. [14] We assume that the more the water fluctuations between periods are important, the more ecosystems integrity is affected. [15]

2.2.2 The thermal producer

The thermal player produces electricity using a classical thermal plant. The operation cost of thermal generation is mostly dominated by the fuel cost which has a shape of quadratic function. Hence, the production process of q_t^T units of electricity involves decreasing returns [16]:

$$C_t^T(q_t^T) = \frac{1}{2}c(q_t^T)^2, \tag{4}$$

where c is strictly positive constant.

13. Without loss of generality we assume that each unit of water released from the dam allows the generation of one unit of electricity. Ambec and Doucet (2003) assumed that one unit of water generates α units of electricity ($\alpha > 0$).

14. $\gamma > 0$

15. Dakhlaoui and Moreaux (2004) assumed a quadratic storage cost that is the difference between the current stock S_t and an exogenous one S^*.

16. See Djurovic et al. (2012), Aydin et al. (2017), Damodaran and Sunil Kumar (2018), Bushnell (2003), Genc and Thille (2017), Crampes and Moreaux (2001), Dakhlaoui and Moreaux (2007) and De Villemeur and Vinella (2008).

2.3 Optimisation Problems of Thermal and Hydro operators

The instantaneous profit function of the operator i, $i \in \{H, T\}$, at t is written as the difference between total revenues from selling and the total cost function:

$$\pi_t^i = (\tilde{a}_t - (q_t^T + q_t^H))q_t^i - C_t^i, \ \forall i \in \{H, T\}. \tag{5}$$

We assume that in the beginning of each period, each player decides the optimal electricity quantity that maximizes the expected utility of his profit. Utility functions are characterized by constant absolute risk aversion, i.e., $U_i(\pi_t^i) = -e^{-A\pi_t^i}$. The positive parameter A is the constant absolute risk aversion of Arrow-Pratt that measures the intensity of risk aversion of the players. $U(.)$ is a continuous, strictly increasing and concave function. The marginal utility is then a decreasing function, i.e., for a given increase in profit, usefulness is lower as earnings increase. Given the exponential function it can be shown that the maximization of the expected utility of the random profit of producer i at time t is equivalent to the maximization of the following equation: [17]

$$W_t^i(\pi_t^i) = E_t(\pi_t^i) - \frac{A}{2}Var(\pi_t^i), \ \forall i \in \{H, T\}, \tag{6}$$

We assume that players have a symmetric risk aversion level. Besides, the right side of equation (6) captures the weight that the decision maker attaches to risk.

2.3.1 Hydro producer's problem

Using equations (1) and (6) and the demand uncertainty specificities, the instantaneous expected utility of the profit of H is defined as follows:

$$W_t^H = \left[a_t - b(q_t^H + q_t^T)\right] q_t^H - \frac{\gamma}{2}(S_t - S_{t+1})^2 - \frac{A}{2}\sigma^2(q_t^H)^2. \tag{7}$$

The Hydro producer chooses the electricity path (with infinite horizon) $\{q_t^H\}_{t=0,\ldots\infty}$ solution to the dynamic optimization problem that follows:

$$\begin{cases} \max\limits_{\{q_t^H\}_{t=0..\infty}} \sum_{t=0}^{\infty} \beta^t \{(a_t - bQ_t)q_t^H - \frac{\gamma}{2}(S_t - S_{t+1})^2 - \frac{A}{2}\sigma^2(q_t^H)^2\} \\ \text{s.t.} \qquad S_{t+1} = S_t - q_t^H + f_t, \ \forall t, \\ \qquad\qquad S_0 \text{ given.} \end{cases} \tag{8}$$

17. Larue and Yapo (2000) considered the same utility function and expected profit specifications while they assumed the response function of the risk adverse competitor as uncertain.

We define S_0 as the initial stock of water, β is the discount factor, q_t^H is the control variable and S_{t+1} is the state variable. The Lagrangian function associated to the optimisation problem of H is :

$$L = \sum_{t=0}^{\infty}\{\beta^t\{a_t - bQ_t)q_t^H - \frac{\gamma}{2}(S_t - S_{t+1})^2 - \frac{A}{2}\sigma^2(q_t^H)^2 + \lambda_t(S_t - q_t^H + f_t - S_{t+1})\} \tag{9}$$

λ_t represents the state covariable associated to the dynamic stochastic constraint of water storage. This problem admits a finite solution (Ljungqvist and Sargent (2004)).

2.3.2 Thermal producer's problem

In each period, the thermal player chooses the production level that maximises the expected utility of his profit defined as follows:

$$\max_{\{q_t^H\}} \; W_t^T = \left[a_t - b(q_t^H + q_t^T)\right] q_t^T - \frac{1}{2}c.(q_t^T)^2 - \frac{A}{2}.(q_t^T)^2\sigma^2. \tag{10}$$

3 Cournot equilibrium with environmental regulation of hydro production

In this section we determine the analytic resolution of the Cournot-Nash equilibrium related to the dynamic game between risk adverse producers T and H in the presence of an environmental cost for hydro producer to pay. The first order condition (FOC) related to the maximisation of the expected utility of the thermal producer leads to the reaction function of T to the strategy of his competitor:

$$q_t^T = R_t^T(q_t^H) = \frac{a_t}{2b + c + A\sigma^2} - \frac{b}{2b + c + A\sigma^2}q_t^H. \tag{11}$$

The FOC associated to the optimisation problem of H, according to the control variable, q_t^H, and to the state variable, S_{t+1}, are as follows:

$$a_t - (2b + A\sigma^2)q_t^H - bq_t^T = \lambda_t, \tag{12}$$

$$\lambda_t + \gamma(S_{t+1} - S_t) = \beta\frac{\partial V(S_{t+1})}{\partial S_{t+1}}. \tag{13}$$

Optimality is obtained through two conditions, the marginal benefit of a unit of water engaged in the production process at t equals the shadow price of a unit of potential energy stored at t (water value), equation (13), and the marginal cost of stored water (which is the shadow price of a unit of potential energy stored at t plus the marginal storage cost) equals the actual marginal value of retained water, equation (14). The intertemporal reaction function of H, derived from those previous FOC, is as follows:

$$q_t^H = \frac{q_{t-1}^H}{\beta} - \frac{a_{t-1} - \beta a_t + \gamma(f_{t-1} - \beta f_t) - b(q_{t-1}^T - \beta q_t^T)}{\beta(2b + \gamma + A\sigma^2)}. \tag{14}$$

The analytic resolution of this game is presented in the following proposition.[18]

Proposition 1:

The Cournot-Nash equilibrium of the dynamic game in the wholesale electricity market is given by the following expressions:[19]

$$q_t^{T*} = \frac{a_t(\gamma + b + A\sigma^2) - b\gamma f_t}{(\gamma + 2b + A\sigma^2)(c + 2b + A\sigma^2) - b^2},$$

$$q_t^{H*} = \frac{a_t(c + b + A\sigma^2) + \gamma(2b + c + A\sigma^2) f_t}{(\gamma + 2b + A\sigma^2)(c + 2b + A\sigma^2) - b^2},$$

$$P_t^* = \frac{a_t(\gamma + b + A\sigma^2)(b + c + A\sigma^2) - \gamma(b + c + A\sigma^2) b f_t}{(\gamma + 2b + A\sigma^2)(c + 2b + A\sigma^2) - b^2}.$$

This equilibrium exists if and only if[20] $f_t < \overline{f_t}$, with $\overline{f_t} = \dfrac{a_t(\gamma + b + A\sigma^2)}{b\gamma}$.

We notice first of all, that the equilibrium existence condition is directly linked to the presence of the environmental cost. The inflow amount would not be restricted if there was no environmental policy. Second, the more the demand is volatile and/or the more firms are risk adverse, the less the inflow amount is restricted. Furthermore, the more (less) the cost parameter, c, is high, the less (more) the thermal plant is used and the hydro producer substitutes partially the residual demand. More precisely, the effect of c on the thermal production is more than twice as high as its effect on the hydro production, $|\frac{\partial q_t^{T*}}{\partial c}| = \frac{\partial q_t^{H*}}{\partial c}(\frac{\gamma + 2b + A\sigma^2}{b})$, consequently, the more (less) c is high, the less (more) the electricity supply is secure, $\frac{\partial Q_t^*}{\partial c} < 0$.[21] We notice also that, the more the actual water inflows are high, the less the decrease of the total production following an increase in the thermal cost parameter is important, in fact, $|\frac{\partial Q_t^*}{\partial c}|$ decreases with f_t. As a matter of fact, the substituted units by the hydropower producer are more important when the water is more available. Besides, the more the demand is uncertain and/or the more

18. The proof is presented in the technical appendix.

19. The total Nash equilibrium output is given by: $Q_t^* = \frac{a_t(\gamma + 2b + c + 2A\sigma^2) + \gamma(b + c + A\sigma^2) f_t}{(\gamma + 2b + A\sigma^2)(c + 2b + A\sigma^2) - b^2}$.

20. The condition needed to have $q_t^{T^*}$ and p_t^* strictly positive.

21. $\frac{\partial Q_t^*}{\partial c} = \frac{(\gamma + b + A\sigma^2)(b\gamma f_t - a_t(\gamma + b + R))}{((\gamma + 2b + A\sigma^2)(c + 2b + A\sigma^2) - b^2)^2}$

the producers are risk adverse, the more the electricity is expensive, $\frac{\partial P_t^*}{\partial A\sigma^2} > 0$, and the less the total production is important, $\frac{\partial Q_t^*}{\partial A\sigma^2} < 0$.

Proposition 2:

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

(i) If $\gamma \leq c$, *then* $\forall f_t, \quad q_t^{H^*} > q_t^{T^*}$.

$$\textit{(ii) If } \gamma > c, \textit{ then } \begin{cases} \textit{if} \quad f_t \in \left]0, \frac{a_t(\gamma - c)}{\gamma(c + 3b + A\sigma^2)}\right], & \textit{then} \quad q_t^{H^*} \leq q_t^{T^*}, \\ \\ \textit{if} \quad f_t \in \left]\frac{a_t(\gamma - c)}{\gamma(c + 3b + A\sigma^2)}, \overline{f_t}\right[, & \textit{then} \quad q_t^{H^*} > q_t^{T^*}. \end{cases}$$

According to (i), when the environmental cost parameter is inferior to the thermal cost one, the market production is predominately hydraulic. In fact, if c is greater than γ, T's marginal cost is necessarily superior to the marginal cost of H, i.e., $C_m^T(.) > C_m^H(.)$.[22] Consequently, T will reach his maximal expected utility and will stop producing at an optimal quantity that is lower to H's optimal one.

According to (ii), when the overuse or the underuse the current inflows cost more than the thermal production, the mix-energy scheduling depends on the water inflows level. Let's note first that $\frac{a_t(\gamma - c)}{\gamma(c + 3b + A\sigma^2)}$ is the inflow level for which T's marginal cost equals H's marginal cost, $C_m^T(q_t^{T^*}) = C_m^H(q_t^{H^*})$. If the inflows are abundant enough, we necessarily have $C_m^T(q_t^{T^*}) > C_m^H(q_t^{H^*})$. As a matter of fact, the more water is abundant and the more H is incited to increase his production and for this relatively high environmental cost, it is more expensive for H to store a supplementary unit of water than for T to produce an additional unit. Thus, the market is predominantly satisfied with hydraulic energy. Otherwise, in a water scarcity situation, we necessarily have, $C_m^T(q_t^{T^*}) \leq C_m^H(q_t^{H^*})$ and T has the biggest market share. In such situation, it is more expensive for H to release an additional unit of water, that is required to increase the gap between outflows and inflows, than for T to produce a supplementary unit. In addition, as water inflows are scarce, H is constrained to produce an amount of energy that is proportional to the water scarcity degree. Thus, T has the biggest market share. We notice also that the more the demand is uncertain and/or the more the players are risk adverse and the scarcest the water needs to be in order to insure T's production predominance.

22. If the firm i produces more than the firm j, it means that for the optimal production of j, $q_t^{j^*}$, while the marginal cost of j equals to the marginal gains, the marginal cost of i is superior to the marginal gains. A supplementary unit produced by H increases his total cost by $\gamma(q_t^H - f_t) + A\sigma^2 q_t^H$ while a supplementary unit produced by T increases his total cost by $cq_t^T + A\sigma^2 q_t^T$.

3.1 Effect of the water inflows on the equilibrium

While the operator H increases his production when observing a rise in the flow of precipitation, the operator T reduces strategically his own in order to re-establish the equilibrium. As a matter of fact, according to the dynamic constraint on the evolution of water (2), the more the inflows are abundant the more H needs to increase his current production in order to satisfy this dynamic constraint. The increase of the potential risk faced, due to the increase of the production, outweighs the increase of profit expectation. Furthermore, the more the inflows are abundant, the more the total electricity amount is high, $\frac{\partial Q_t^*}{\partial f_t} > 0$. In fact, following one supplementary unit of inflow, the increase of hydroelectricity is more important than the decrease of the thermal quantity, $\frac{\partial q_t^{H^*}}{\partial f_t} > |\frac{\partial q_t^{T^*}}{\partial f_t}|$, and more precisely, $\frac{\partial q_t^{H^*}}{\partial f_t} = (2 + \frac{c + A\sigma^2}{b})|\frac{\partial q_t^{T^*}}{\partial f_t}|$. Therefore, water abundance insures the security in electricity supply and provides a lower electricity price, unlike the water scarcity situation.

3.2 Effect of the environmental cost parameter on the equilibrium

In this section, we examine the effect of a variation in the environmental cost parameter level on the producers' strategies and on the equilibrium.

Proposition 3:

The variations of the equilibrium quantities and the market price within the environmental cost depend on the water availability:

(i) If $f_t \in \left]0,\ f_t^{(\gamma)}\right[$, *then* $\frac{\partial q_t^{H^*}}{\partial \gamma} < 0$, $\frac{\partial q_t^{T^*}}{\partial \gamma} > 0$ *and* $\frac{\partial P_t^*}{\partial \gamma} > 0$,

(ii) if $f_t \in \left[f_t^{(\gamma)},\ \overline{f_t}\right[$, *then* $\frac{\partial q_t^{H^*}}{\partial \gamma} \geq 0$, $\frac{\partial q_t^{T^*}}{\partial \gamma} \leq 0$ *and* $\frac{\partial P_t^*}{\partial \gamma} \leq 0$,

with $f_t^{(\gamma)} = \frac{a_t(c + b + A\sigma^2)}{(c + 2b + A\sigma^2)(2b + A\sigma^2) - b^2}$ and $f_t^{(\gamma)}$ is the inflow amount for which $S_{t+1} = S_t$.

H's reaction towards a variation in the environmental cost parameter, depends on whether he uses partially or totally the current water inflows to produce hydroelectricity at t, which determines if the future stock of water is lower or greater than the current one. According to (i), for a low amount of inflows, a higher environmental cost parameter incite H to increase his water storage. First of all, according to the stock dynamics constraint (equation (2)), if the water engaged in the production process is more important than the inflow amount, then, the future stock of water is necessarily inferior to the current one.[23] Second, according to the storage cost (equation (3)), in order to lower the gap between the future stock and the current one, H needs to increase the future stock by decreasing the current production[24]. We can conclude that the expected benefit of an additional unit produced at t is inferior to its opportunity cost, which is the potential expected gain if this unit is stored to $t+1$. Thus, a higher level of γ promotes intertemporal transfer of water from t to $t+1$ in a water scarcity situation. As a strategic reaction, the player T rises thermal production and satisfies partially the residual demand.[25] The substitution of the costless hydroelectricity, due to the intertemporal water transfer, with costly thermal electricity, lowers indeed ecosystems alteration but rises the air pollution and the market price. Despite the fact that ecosystems integrity is promoted at the expense of air quality, in terms of production units, the gain in securing the surrounding ecosystems is more important than the loss in air quality. As a matter of fact, the thermal firm satisfies less than the half of the residual demand, $\dfrac{\partial q_t^{T^*}}{\partial \gamma} = \dfrac{b}{2b+c+A\sigma^2}|\dfrac{\partial q_t^{H^*}}{\partial \gamma}|$.

According to (ii), in a situation of water abundance, i.e. the optimal quantity of water used is less important than the current inflow, the increase of the environmental cost parameter induces H player to deviate from his initial equilibrium strategy with increasing his current hydroelectricity production, otherwise his expectation in terms of utility declines. Thus, a higher level of γ minimizes the strategical storage of water and consequently lowers the surrounding ecosystems alteration, diminishes air pollution with less thermal production units and lowers the market price. In addition, the more the demand is uncertain and/or the more the players are risk adverse, the less restrictive the condition related to water abundance is. As a matter of fact, with a level of risk[26] R' that exceeds R, we necessarily have $f_t^{(\gamma)}(R') < f_t^{(\gamma)}(R)$.

Moreover, in order to establish a precise environmental statement, the regulation authority needs to compare, using appropriate criteria, the importance of an avoided unit of surrounding ecosystem alteration to an additional unit of air polluting production, in the whole ecosystem functioning. We conclude that, under some hypothesis[27], realising the environmental goal related to ecosystems integrity has necessarily, through the market mechanisms, negative repercussions on air pollution which is the other source of

23. If $f_t \leq q_t^H$ then $S_{t+1} \leq S_t$.

24. The proof of this conclusion is that the storage cost form implies that when $(S_{t+1} - S_t)$ is negative, the more it increases the more $(S_{t+1} - S_t)^2$ decreases.

25. The strategical behaviour of H, based on an intertemporal matter, affects T's decision despite the fact that he has only static considerations, which represents a classical result.

26. The risk parameter is: $R = A\sigma^2$.

27. Linked to water scarcity situation.

environmental degradation. In order to limit air quality degradation, we will add in the next section to the market modelling a taxation policy, intended for the thermal producer.

4 Cournot equilibrium in the presence of an environmental cost for H and a taxation policy for T

In this section, we consider the existence of an environmental policy that targets to limit the use of the thermal plant. We consider that the player T is subject to an ad-valorem tax represented by x. The optimisation problem of T is as follows:

$$\max_{q_t^T} W_t^{T,x}(\pi_t^{T,x}) = \left[a_t - b(q_t^H + q_t^T)\right] q_t^T - \frac{1}{2}c.(q_t^T)^2 - \frac{A}{2}.(q_t^T)^2\sigma^2 - x.q_t^T.$$

The reaction function of T with respect to his rival production decision is:

$$R_t^{T,x}(q_t^H, x) = \frac{a_t - x}{2b + c + A\sigma^2} - \frac{b}{2b + c + A\sigma^2} q_t^H. \tag{15}$$

Furthermore, the optimisation problem and the reaction function of H are the same than in the equilibrium without environmental policy described by the equations (8) and (14).

Proposition 4:

The equilibrium of the dynamic game between thermal and hydraulic operators in the wholesale electricity market when both players are subject to environmental policy is given by the following expressions:[28]

$$q_t^{T,x} = \frac{a_t(\gamma + b + A\sigma^2) - x(\gamma + 2b + A\sigma^2) - b\gamma f_t}{(\gamma + 2b + A\sigma^2)(c + 2b + A\sigma^2) - b^2},$$

$$q_t^{H,x} = \frac{a_t(c + b + A\sigma^2) + b.x + \gamma(2b + c + A\sigma^2) f_t}{(\gamma + 2b + A\sigma^2)(c + 2b + A\sigma^2) - b^2},$$

$$P_t^x = \frac{a_t(\gamma + b + A\sigma^2)(c + b + A\sigma^2) + b.x(\gamma + b + A\sigma^2) - \gamma(b + c + A\sigma^2) b f_t}{(\gamma + 2b + A\sigma^2)(c + 2b + A\sigma^2) - b^2}.$$

The Nash equilibrium exists if and only if $f_t \leq \overline{f_t}^x$, with $\overline{f_t}^x = \dfrac{a_t(\gamma + b + A\sigma^2) - x(\gamma + 2b + A\sigma^2)}{b\gamma}$ *and* $x > 0$.

The existence condition shows that in the presence of a taxation policy, the maximal inflows amount required is inferior to the one associated to the equilibrium without taxation policy; $\overline{f_t}^x < \overline{f_t}$. In order to guarantee the possibility of a thermal production, the water inflows available for H have to be lower

28. The total output of the industry at the equilibrium is: $Q_t^x = \dfrac{a_t(\gamma + c + 2b + 2A\sigma^2) - x(\gamma + b + A\sigma^2) + \gamma(c + b + A\sigma^2) f_t}{(\gamma + 2b + A\sigma^2)(c + 2b + A\sigma^2) - b^2}$.

now that T is subject to an additional constraint. Moreover, the more the demand is uncertain and/or the more the producers are risk adverse, the more the electricity is expensive, $\frac{\partial P_t^x}{\partial A\sigma^2} > 0$, and the less the total production is important, $\frac{\partial Q_t^x}{\partial A\sigma^2} < 0$. Furthermore, if the production cost parameter of T is much more important than the environmental cost one, i.e. $c > \gamma + \frac{(\gamma + b + A\sigma^2)^2}{b}$, then the effect of the risk parameter is intensified by the taxation, i.e., $\frac{\partial P_t^x}{\partial A\sigma^2} > \frac{\partial P_t^*}{\partial A\sigma^2}$.

4.1 Effect of the taxation on the equilibrium

The immediate effect of the taxation is the increase of the thermal operating cost, which decreases the polluting production; $\frac{\partial q_t^{T,x}}{\partial x} < 0$ and then $q_t^{T,x} < q_t^{T^*}$. The producer H satisfies partially the residual demand by increasing his production, $|\frac{\partial q_t^{T,x}}{\partial x}| > \frac{\partial q_t^{H,x}}{\partial x}$. The fact that the residual demand is not entirely substituted is due to the choice of H to not rise too much his production in order to guarantee the higher profit utility expectation possible. Thus, under the effect of the taxation, the total production diminishes $\frac{\partial Q_t^x}{\partial x} = Q_t^x - Q_t^* = \frac{-x(\gamma + b + A\sigma^2)}{(\gamma + 2b + A\sigma^2)(c + 2b + A\sigma^2) - b^2}$ and the price increases proportionally to the tax level and this loss in price efficiency is evaluated to : $\frac{\partial P_t^x}{\partial x} = P_t^x - P_t^* = \frac{bx(\gamma + b + A\sigma^2)}{(\gamma + 2b + A\sigma^2)(c + 2b + A\sigma^2) - b^2}$.

Furthermore, the regulator can fully suspend the polluting production with imposing a prohibitive taxation. In fact, the hydraulic operator is in a monopoly situation if the tax reaches it maximal amount; $\overline{x} = \frac{a_t(\gamma + b + A\sigma^2) - b\gamma f_t}{\gamma + 2b + A\sigma^2}$. This particular equilibrium is as following :

$$q_t^{H,\overline{x}} = \frac{a_t - x}{b} = \frac{a_t + \gamma f_t}{\gamma + b + A\sigma^2} \ , \ q_t^{T,\overline{x}} = 0 \ , \ P_t^x = \overline{x} \tag{16}$$

4.2 Effect of the environmental cost parameter on the equilibrium

In this section, we examine first, how the water management strategy of H is affected by the environmental cost parameter now that his competitor is subject to a taxation, second the consequences on T's production strategy and on the market price and finally, the consequences on the negative environmental externalities.

Proposition 5:

The variations of the equilibrium quantities and price within the environmental cost parameter are as following:

(i) If $x > x^{(\gamma)}$*, then* $\forall f_t$, $\frac{\partial q_t^{H^x}}{\partial \gamma} < 0$, $\frac{\partial q_t^{T^x}}{\partial \gamma} > 0$ and $\frac{\partial P^x}{\partial \gamma} > 0$.

$$\text{(ii) If } x \leq x^{(\gamma)}, \text{ then } \begin{cases} \text{If} \quad f_t \in \left]0,\ f_t^{x,(\gamma)}\right[\quad \text{then} \quad \dfrac{\partial q_t^{H^x}}{\partial \gamma} < 0,\ \dfrac{\partial q_t^{T^x}}{\partial \gamma} > 0 \text{ and } \dfrac{\partial P^x}{\partial \gamma} > 0, \\ \\ \text{if} \quad f_t \in \left[f_t^{x,(\gamma)},\ \overline{f_t}^x\right] \quad \text{then} \quad \dfrac{\partial q_t^{H^x}}{\partial \gamma} \geq 0,\ \dfrac{\partial q_t^{T^x}}{\partial \gamma} \leq 0 \text{ and } \dfrac{\partial P^x}{\partial \gamma} \leq 0, \end{cases}$$

$$\text{with } x^{(\gamma)} = a_t \frac{(\gamma + b + A\sigma^2)\left[(c + 2b + A\sigma^2)(2b + A\sigma^2) - b^2\right] - b\gamma(c + b + A\sigma^2)}{(2b + A\sigma^2)\left[(\gamma + 2b + A\sigma^2)(c + 2b + A\sigma^2) - b^2\right]} \text{ and } f_t^{x,(\gamma)} = \frac{a_t(c + b + A\sigma^2}{(c + 2b + A\sigma^2)(2b +}$$

We notice first of all, that while improving air quality rises necessarily the market price, enhancing ecosystems integrity can under some hypothesis reduce the market price. Second, the effect of the storage cost parameter on the equilibrium depends on the tax level and on the inflow amount. According to (i), when the tax level is important enough to exceed a certain threshold denoted by $x^{(\gamma)}$, then it drastically affects T's strategy and consequently the residual demand, addressed to H, is so high that the latter uses necessarily the totality of his current inflows (f_t) and draws on his current stock to produce his initial amount of electricity ($q_t^{H^*}$) plus the additional units to substitute partially the thermal ones ($q_t^{H^x} - q_t^{H^*}$). Thus, the future water stock of H (S_{t+1}) is necessarily inferior to the current one (S_t). Following a potential increase in the storage cost parameter, H needs to lower his current production in order to increase his future stock which reduces the gap with the current stock. Consequently and despite the taxation policy, the market mechanisms leads T to increase his own production in order to substitute partially the decrease of the production of his competitor, $\dfrac{\partial q_t^{T,x}}{\partial \gamma} = -(\dfrac{b}{c + 2b + A\sigma^2})\dfrac{\partial q_t^{H,x}}{\partial \gamma}$. Those additional thermal units represent a relatively small proportion of the residual demand and the more the thermal production is costly and/or the more the market is risky, the smaller this proportion is. In conclusion, despite the important residual demand which requires an amount of water higher than the water inflows of period t, when facing an increase of the storage cost parameter, H produces less, which lower his market share, reduces water level fluctuations, but increases slightly air pollution as well as the market price.

Besides, according to (ii), when the tax level is at the most equal to the threshold specified above, the residual demand addressed to H is low enough so that the strategy of H, following an increase on the environmental cost parameter, depends on the abundance of the actual water inflows and whether it allows strategical storage or not. We denote by $f_t^{x,(\gamma)}$, the precise level of inflows that equals the optimal production of H, this situation represents the most optimal one for ecosystems integrity. Furthermore, if the current water inflow level is lower than $f_t^{x,(\gamma)}$, then H uses all of it and pumps water in order to produce electricity, consequently, when γ increases, H needs to decrease his production in order to increase the future stock, which lowers his total environmental cost. This situation of water scarcity leads to the same results described in (i). Otherwise, if the current water inflow is abundant enough, such that, despite the satisfaction of the residual demand resulting from the taxation of his competitor, H stores strategically water and transfers it to the next period, then, when the environmental cost parameter increases, H optimal strategy is to increase his actual production in order to lower the future water stock, which is needed to minimize the environmental cost and T reacts with lowering his production units. Consequently, in a situation of water abundance coupled with a low taxation level, the increase of the environmental cost parameter promotes the hydroelectricity, minimises biodiversity alteration, lowers air pollution, lowers the market price and increases the total electricity offered.

4.3 Effect of the taxation on the efficiency of the environmental cost addressed to H

In order to establish a statement about environmental efficiency when those measures are applied simultaneously, the effects of taxation and environmental cost need to be analysed conjointly. We will now examine the interactions between both environmental measures, their consequences on the equilibrium and their potential side effects on the environmental benefits. Let's note that prioritizing natural flow regime through environmental cost minimizes necessarily the taxation efficiency on lowering air pollution and enhances the price rise due to the taxation. In fact, with a level γ' which is superior to γ, we have $|\frac{\partial q_t^{T,x}}{\partial x}(\gamma')| < |\frac{\partial q_t^{T,x}}{\partial x}(\gamma)|$ and $\frac{\partial P_t^x}{\partial x}(\gamma') > \frac{\partial P_t^x}{\partial x}(\gamma)$. However, the effect of the taxation policy on the efficiency of the ecosystems integrity policy depends essentially on two aspects: first, the amount of the residual demand that H needs to satisfy which is linked to the taxation degree that T is facing, and second, H's ability to substitute thermal unities which depends on the available amount of water (proposition 5). We distinguish three different cases.

Proposition 6: [29]

(j) If $x > x^{(\gamma)}$ *or, if* $x \leq x^{(\gamma)}$ *and* $f_t \in \left]0,\ f_t^{x,(\gamma)}\right[$ *then* $|\frac{\partial q_t^{H,x}}{\partial \gamma}| > |\frac{\partial q_t^{H^*}}{\partial \gamma}|$, $\frac{\partial q_t^{T,x}}{\partial \gamma} > \frac{\partial q_t^{T^*}}{\partial \gamma}$ *and* $\frac{\partial P_t^x}{\partial \gamma} > \frac{\partial P_t^*}{\partial \gamma}$.

(jj) If $x \leq x^{(\gamma)}$ *and* $f_t \in \left[\ f_t^{(\gamma)},\ f_t^{x,(\gamma)}\right[$ *then* $\frac{\partial P_t^x}{\partial \gamma} > 0$ *and* $\frac{\partial P_t^*}{\partial \gamma} < 0$.

29. $\frac{\partial q_t^{H,x}}{\partial \gamma} - \frac{\partial q_t^{H^*}}{\partial \gamma} = \frac{-xb(c+2b+A\sigma^2)}{((\gamma+2b+A\sigma^2)(c+2b+A\sigma^2)-b^2)^2}$, $\frac{\partial q_t^{T,x}}{\partial \gamma} - \frac{\partial q_t^{T^*}}{\partial \gamma} = \frac{xb^2}{((\gamma+2b+A\sigma^2)(c+2b+A\sigma^2)-b^2)^2}$, $\frac{\partial P_t^x}{\partial \gamma} - \frac{\partial P_t^*}{\partial \gamma} = \frac{xb^2(c+b+A\sigma^2)}{((\gamma+2b+A\sigma^2)(c+2b+A\sigma^2)-b^2)^2}$ *and* $\frac{\partial Q_t^x}{\partial \gamma} - \frac{\partial Q_t^*}{\partial \gamma} = \frac{-xb(c+b+A\sigma^2)}{((\gamma+2b+A\sigma^2)(c+2b+A\sigma^2)-b^2)^2}$.

(jjj) If $x \leq x^{(\gamma)}$ *and* $f_t \in \left[\ f_t^{x,(\gamma)},\ \overline{f_t}^x\right]$ *then* $\frac{\partial q_t^{H,x}}{\partial \gamma} < \frac{\partial q_t^{H^*}}{\partial \gamma}$, $|\frac{\partial q_t^{T,x}}{\partial \gamma}| < |\frac{\partial q_t^{T^*}}{\partial \gamma}|$ *and* $|\frac{\partial P_t^x}{\partial \gamma}| < |\frac{\partial P_t^*}{\partial \gamma}|$.

According to (j), H's reaction towards the environmental cost parameter is intensified by the taxation. This occurs in a situation where the taxation level is significantly high or in a situation where the current inflows are significantly scarce. In those situations, in order to substitute residual demand, H player rises considerably his production by using entirely the current inflow and drawing on the stored water. As a matter of fact, the higher the taxation level is, the more important the residual demand addressed to H is, and satisfying it requires from H to diverge more significantly from the current inflows amount. In addition, the more H diverge from the current inflows amount and the more significant the gap between inflows and outflows is. Thus, in order to reach optimality following an increase in γ, the more H's initial use of water is excessive and the more important the units that he needs to store are important. In conclusion, following the taxation of his competitor, H becomes more sensitive to the environmental cost and decreases more significantly his production with respect to γ, $|\frac{\partial q_t^{H,x}}{\partial \gamma}| > |\frac{\partial q_t^{H^*}}{\partial \gamma}|$. Besides, despite the high taxation level, the market mechanisms, through an additional residual demand, imply that T's reaction to the environmental cost parameter is amplified in the presence of a taxation policy. Indeed he rises more importantly his production, $\frac{\partial q_t^{T,x}}{\partial \gamma} > \frac{\partial q_t^{T^*}}{\partial \gamma}$, and the market price is consequently higher than in the case without taxation. In conclusion, the presence of a taxation policy in those situations promotes significantly the natural flow regime which enhances ecosystems integrity at the expense of the efficiency of the taxation to decrease air quality.

According to (jj), for this medium inflow amount, under a taxation, H needs to use all of his current inflow while without taxation H uses it partially.

However, according to (jjj), in a situation of water abundance coupled with a relatively low taxation level, the taxation policy attenuates the reaction of H towards the environmental cost. In this situation H uses partially his current inflow amount of water, and following an increase in γ, H increases his production in order to minimise the gap between inflows and outflows. The more the regulator increases the taxation level, the less H is sensitive to his environmental cost. As a matter of fact, following an increase of his rival taxation level, the additional units that H produces, to minimise the gap between inflows and outflows, becomes less important. The abundance of water increases H's space for manoeuvre as well as H's incentives for opportunistic behaviour. The expected gains from decreasing his production and increasing his strategical storage are superior to the related additional environmental cost. In this precise situation, the environmental benefits in terms of ecosystems integrity are lowered by the strategical storage of H following the taxation of his competitor, which attenuates the improvements of air quality and limits the electricity price decrease.

In conclusion, when those two environmental policies are present simultaneously, realising one environmental goal has necessarily, through the market mechanisms, repercussions on the efficiency of the policy to limit the other source of degradations. While the ecosystems integrity instrument minimizes necessarily the taxation efficiency, the taxation can whether enhance or limit the efficiency of the ecosystems integrity policy.

5 Conclusion

In this paper, we analyse the effect of an environmental policy that targets to enhance ecosystems integrity as well as air quality in the wholesale electricity market. We developed a dynamic Cournot game between a hydro and a thermal risk adverse electricity producers under demand uncertainty. In our first model, we studied the equilibrium strategies of both producers when the regulation authority imposes an environmental cost that the hydro producer needs to pay in order to minimize water level fluctuations. We conclude that the behaviour of the latter towards such a policy depends on whether he uses partially or totally the current water inflows. In addition, in a water scarcity situation, ecosystems integrity is promoted at the expense of air quality and market price efficiency. Nevertheless, the more the demand is uncertain and/or the more the players are risk adverse, the more the environmental cost parameter is likely to minimize both environmental degradations at the expense of the price efficiency. Furthermore, we add in our second model a taxation policy that targets to increase air quality. The demand uncertainty as well as the intensity of risk aversion lower the taxation efficiency. Indeed, the more the risk faced is high, the more its importance, for the thermal producer as a choice criterion, increases at the expense of the tax. However, if the thermal cost parameter is inferior or not too much higher than the storage cost, then, the increase of the price due to the taxation is lowered by the risk parameter. In addition, we demonstrate that while improving air quality rises necessarily the market price, enhancing ecosystems integrity can under water abundance hypothesis reduce the price. Nevertheless, the behaviour of the hydro producer towards the environmental cost depends crucially on the taxation level which determines how important the residual demand is. Indeed, in a situation of water abundance coupled with a low taxation level, the environmental cost minimises surrounding biodiversity alteration, lowers air pollution as well as the market price. Otherwise, ecosystems integrity is promoted at the expense of air quality and market price efficiency. Moreover, in order to establish a statement about the environmental policy efficiency, we examine interactions between both environmental measures and their potential side effects. We demonstrate that prioritizing natural flow regime minimises necessarily the taxation efficiency on lowering air pollution and emphasizes the price rise due to the taxation. Nevertheless, the effect of the taxation policy on the efficiency of the ecosystems integrity policy depends on the hydro producer's ability to substitute thermal units. In a situation where the taxation level is important or the water is scarce, the taxation policy promotes significantly ecosystems integrity. However, in a situation of water abundance coupled with a relatively low taxation level, the environmental benefits in terms of ecosystems integrity are lowered by the taxation policy. Indeed, the hydro producer, due to his important space of manoeuvre, has incentives for opportunistic behaviour. Besides, in order to establish a precise environmental statement, the regulation authority needs to insure two actions. First, to compare, using appropriate criteria, the importance of an avoided unit of surrounding ecosystem alteration to an avoided unit of air polluting production, in the whole ecosystem functioning. Second, to choose an appropriate global environmental policy with optimal policies parameter levels. This choice has to be crucially based on the degree of water availability, on the side effects associated to the simultaneousness of both policies in terms of limiting each other's efficiency and their consequences on the electricity price, and finally and more importantly, on the order of priorities of the regulation authority in terms of environmental objectives and market price. However, it is important to note that those findings are based on our initial hypothesis and that integrating inflows uncertainty may further refine our results.

6 Technical Appendix

Equation (14) is equal to:

$$\gamma(S_t - S_{t+1}) - \lambda_t - \beta\gamma(S_{t+1} - S_{t+2}) + \beta\lambda_{t+1} = 0. \tag{17}$$

Equation (13) at $t+1$ becomes:

$$a_{t+1} - (2b + A\sigma^2)q^H_{t+1} - bq^T_{t+1} = \lambda_{t+1}. \tag{18}$$

Substituting the equations (18) and (2) into the equation (17) gives:

$$\gamma(q^H_t - f_t) - a_t + (2b + A\sigma^2)q^H_t + bq^T_t - \beta\gamma(q^H_{t+1} - f_{t+1}) + \beta(a_{t+1} - (2b + A\sigma^2)q^H_{t+1} - bq^T_{t+1}) = 0. \tag{19}$$

The equation (19) is equivalent to:

$$q_{t+1}^H = \frac{q_t^H}{\beta} - \frac{a_t - \beta a_{t+1} + \gamma(f_t - \beta f_{t+1}) - b(q_t^T - \beta q_{t+1}^T)}{\beta(2b + \gamma + A\sigma^2)}. \tag{20}$$

At t, the equation (20), becomes as follows, which represents the reaction function of H:

$$q_t^H = \frac{a_t + f_t - bq_t^T}{(2b + \gamma + A\sigma^2)} - \frac{a_{t-1} + \gamma f_{t-1} - bq_{t-1}^T}{\beta(2b + \gamma + A\sigma^2)} + \frac{q_{t-1}^H}{\beta}.$$

In order to solve the dynamic game equilibrium, we substitute the reaction function of T into equation (19), which gives:

$$q_t^H = \beta q_{t+1}^H - \beta\frac{\gamma\theta}{\alpha} f_{t+1} + \frac{\gamma\theta}{\alpha} f_t + \frac{\sigma}{\alpha} a_t - \beta\frac{\sigma}{\alpha} a_{t+1}, \tag{21}$$

with $\alpha = (\gamma + 2b + A\sigma^2)(c + 2b + A\sigma^2) - b^2$, $\theta = c + 2b + A\sigma^2$ and $\sigma = \theta - b$.

Now, using iteration technique, we, first of all, solve the equation (21) and we obtain the five following equivalent equations:

1. $q_t^H = \beta(\beta q_{t+2}^H - \beta\frac{\gamma\theta}{\alpha} f_{t+2} + \frac{\gamma\theta}{\alpha} f_{t+1} + \frac{\sigma}{\alpha} a_{t+1} - \beta\frac{\sigma}{\alpha} a_{t+2}) - \beta\frac{\gamma\theta}{\alpha} f_{t+1} + \frac{\gamma\theta}{\alpha} f_t + \frac{\sigma}{\alpha} a_t - \beta\frac{\sigma}{\alpha} a_{t+1}$
2. $q_t^H = \beta^2 q_{t+2}^H - \beta^2\frac{\gamma\theta}{\alpha} f_{t+2} - \beta^2\frac{\sigma}{\alpha} a_{t+2} + \frac{\gamma\theta}{\alpha} f_t + \frac{\sigma}{\alpha} a_t$
3. $q_t^H = \beta^2(\beta q_{t+3}^H - \beta\frac{\gamma\theta}{\alpha} f_{t+3} + \frac{\gamma\theta}{\alpha} f_{t+2} + \frac{\sigma}{\alpha} a_{t+2} - \beta\frac{\sigma}{\alpha} a_{t+3}) - \beta^2\frac{\gamma\theta}{\alpha} f_{t+2} - \beta^2\frac{\sigma}{\alpha} a_{t+2} + \frac{\gamma\theta}{\alpha} f_t + \frac{\sigma}{\alpha} a_t$
4. $q_t^H = \beta^3 q_{t+3}^H - \beta^3\frac{\gamma\theta}{\alpha} f_{t+3} - \beta^3\frac{\sigma}{\alpha} a_{t+3} + \frac{\gamma\theta}{\alpha} f_t + \frac{\sigma}{\alpha} a_t$
5. $q_t^H = \beta^4 q_{t+4}^H - \beta^4\frac{\gamma\theta}{\alpha} f_{t+4} - \beta^4\frac{\sigma}{\alpha} a_{t+4} + \frac{\gamma\theta}{\alpha} f_t + \frac{\sigma}{\alpha} a_t$

Then, for $T > t + 4$, q_t^H is written as follows:

$$q_t^H = \beta^T(q_{t+T}^H - \frac{\gamma\theta}{\alpha} f_{t+T} - \frac{\sigma}{\alpha} a_{t+T}) + \frac{\gamma\theta}{\alpha} f_t + \frac{\sigma}{\alpha} a_t. \tag{22}$$

When T goes to infinity, β^T goes to zero ($\beta < 1$) and hence the the equation (22) becomes:

$$q_t^H = \frac{\gamma\theta}{\alpha} f_t + \frac{\sigma}{\alpha} a_t.$$

Finally, substituting γ, θ and α by their values, we obtain the optimal production quantity of H at t:

$$q_t^{H^*} = \frac{a_t(c + b + A\sigma^2) + \gamma(c + 2b + A\sigma^2) f_t}{(\gamma + 2b + A\sigma^2)(c + 2b + A\sigma^2) - b^2}.$$

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