Long-term contracting in hydro-thermal electricity generation: welfare and environmental impact

Etienne Billette de Villemeur* Annalisa Vinella†

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Abstract

We consider electricity generation industries where thermal operators imperfectly compete with hydro operators that manage a (scarce) water stock stored in reservoirs over a natural cycle. We explore how the exercise of *intertemporal* market power affects social welfare and environmental quality. We show that, as compared to the outcome of spot markets, long-term contracting either exacerbates or alleviates price distortions, depending upon the consumption pattern over the water cycle. Moreover, it induces a second-order environmental effect that, in the presence of a thermal competitive fringe, is critically related to the thermal market shares in the different periods of the cycle. We conclude by providing policy insights.

Keywords: Hydropower; Thermal power; Water allocation; Environmental externalities; Long-term contracts

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*Toulouse School of Economics (IDEI & GREMAQ)

†University of Bari (DSEMM). *Corresponding author.* Address: Università degli Studi di Bari, Facoltà di Economia, Dipartimento di Scienze economiche e metodi matematici, Via C. Rosalba 53, 70124 Bari (Italy). Phone: +39 0805049101. Fax: +39 0805049149. E-mail: a.vinella@dse.uniba.it

1 Introduction

Hydropower is widespread. It is produced by a total of $27,000$ generating units belonging to $11,000$ power stations located in about 150 countries all over the world.[1] Yet, excluding cases like Paraguay, where the quantity of hydropower produced amounts to ten times the national consumption of electricity, and Norway, where more than 98% of electricity is produced from hydro sources, hydropower constitutes a relatively small fraction of total generated power in most countries.[2] To be precise, the hydro share lies generally far below 50% of the overall power-generation mix, with a world average being about 16%.[3] Notwithstanding, this share is likely to play an important role in the functioning of electricity markets, due to the possibility of hydro-based units being able to freely allocate water across time periods.[4] This appears to be of utmost importance in contexts where demand and, hence, price vary over time.

Electricity consumption actually follows daily, weekly and seasonal cycles. Despite technological progress, nuclear plants do not yet exhibit enough flexibility to "load follow."[5] In practice, given their low marginal costs, nuclear plants are typically used as a base-load source running constantly over time, under the "merit order" system that is, by now, in place in most power industries. As a result, even in countries that are endowed with nuclear stations,[6] cyclical peak loads are met by other electricity sources *i.e.*, hydro and thermal power plants. The latter are essentially fossil-fuel-burning power plants releasing polluting emissions. This suggests that, in electricity markets, the strategic behaviour of hydro producers is likely to have a non-negligible impact on both price patterns and environmental outcomes. Here is the exact focus of our paper.

Specifically, in our study, we look at situations in which a hydro producer imperfectly competes with a thermal sector that can have a more or less competitive structure. Hydro plants use stocks of water stored in reservoirs. The latter are filled by natural inflows from different possible sources, such as running water from the rivers, rainfall, melting snow and ice. Replenishment occurs periodically according to a natural cycle, over which the water reserve is constituted, and then progressively released for production till exhaustion. A new cycle starts as the stock is renewed.[7] By contrast, thermal technology exhibits

[1] Figures from the International Hydropower Association (compare Crampes and Moreaux [7]).

[2] See Apergis and Payne [1] for recent data on energy in South America as well as Johnsen [13] for details about the Norvegian Electric Market. Further examples of countries where hydropower is especially abundant are Brazil, Canada, Switzerland and Venezuela.

[3] Source: International Energy Agency [3].

[4] By contrast, total output cannot be adjusted. On hydro-dominated electricity markets see Rangel [15].

[5] On this aspect see the positions of the UK Ministry for Energy, in the Energy Review Consultation [16], p.60 and p.68.

[6] Though of similar importance, nuclear power is much less widespread than hydropower. In 2008, with 439 nuclear units operating in 30 countries, the nuclear power's share of worldwide electricity generation was about 14%. Source: International Atomic Energy Agency [11].

[7] Hydropower plants also exist that rely upon pump storage, rather than natural storage. According

no seasonality. However, thermal plants use fuels like gas and coal, and thus generate negative environmental externalities.

New Zealand is a particularly good example of a country displaying a power-generation mix with these characteristics. Indeed, in New Zealand, electricity is essentially produced by a thermal firm (22% gas and 12% coal) and a State-owned Enterprise (ECNZ) that manages the two major reservoir-storage systems, comprised of a series of dams and powerhouses mainly located on the rivers (55%) . This is not the sole example though. In America, a significant amount of hydroelectric-generation capacity (though less important than in New Zealand) coexists with thermal stations in the western U.S. Most hydro plants, concentrated in the Pacific Northwest and California, are controlled by a single (public) firm, the Bonneville Power Administration, that is in charge of marketing the electricity produced by federally owned reservoirs along the Columbia River system. Furthermore, roughly 40% of power in the Chilean Sistema Interconectado Central is produced by thermal plants, the reminder is hydro-generated, mainly by rainfall water. In Europe, countries that rely upon a hydro-thermal mix are, for instance, Italy and Finland, where most reservoirs are situated nearby the mountains and filled by melting snow and ice. In Italy, hydro and thermal plants provide about 13% and 77%, respectively, of total electricity; in Finland, about 19% and 50%, respectively.[8]

The markets described above are all imperfectly competitive. From Crampes and Moreaux [7] (CM hereafter) we learn that, in frameworks where electricity is generated by imperfectly competing thermal producers and hydro producers, the market outcome depends on whether or not the latter exert a subtle form of *intertemporal* market power. Indeed, not only can hydro producers raise scarcity rents by appropriately scheduling water releases over the horizon of the natural cycle (this follows from the overall scarcity of the water reserves together with the possibility to store water at zero operating cost). They can also act as "Stackelberg leaders" *vis-à-vis* the thermal competitors because time irreversibility (together with the inelasticity and the scarcity of water reserves) provides a natural commitment device for them to produce more in the later periods of the water cycle. Actually, as pointed out by Murphy and Smeers [14], the former situation is tantamount to having hydro producers sell output under *long-term contracts*, the whole production profile being fixed at the outset of the market game. The latter situation rather mirrors the functioning of *spot markets*, where hydro producers can revise their strategy in each period.

CM disclose the implications that the hydro producers' strategic behaviour has on

to the International Hydropower Association [12], pump-storage capacity is below 150 GW. This is about 1/6 of the actual installed conventional hydro capacity. We do not consider pump storage because it raises specific issues, the analysis of which would be beyond the scope of our study.

[8] In New Zealand, the remainder of power comes from geothermal sources, wind and biomass. In Italy, it is produced by wind, photovoltaic and geothermal plants, whereas in Finland it is generated by nuclear stations.

the performance of hydro-thermal power oligopolies. They do not consider the problems related to environmental damage, and as such, these problems and consequences are neglected in their studies. In fact, an important characteristics of the thermal process, which is based on the use of hydrocarbons, is that it releases polluting emissions. It follows that, in hydro-thermal electricity markets, not only the strategic behaviour of hydro producers affects social welfare, but also the externalities induced by the thermal activity.[9]

It is well known that, in markets where environmental externalities are present, imperfect competition can actually lead to higher social welfare than perfect competition. This is because the exercise of market power acts essentially as an environmental tax, downsizing polluting activities (compare Barnett [3], for instance). In a similar fashion, the strategic advantage of the hydro producer may be potentially beneficial, as it can induce a reduction in thermal production. In the context we explore, however, a complication follows from the inelasticity and the scarcity of the water reserve. Indeed, within the water cycle, any increase in hydro production in one period is associated with an equal decrease in another period. Under these circumstances, it is far from obvious to which outcome the interaction between hydro producers' strategic behaviour and environmental externalities will lead.

The ultimate purpose of our work is to study whether, and how, the adoption of long-term contracts affects social welfare and environmental quality in electricity industries with a hydro-thermal generation mix. To do so, we embody the release of thermal emissions into the model of open and closed-loop Cournot competition elaborated by CM.[10] Despite resorting to the same representation, we nonetheless provide a richer interpretation as compared to CM. Similarly to Murphy and Smeers [14], we interpret open-loop competition as an institutional setting in which output is sold under long-term contracts. By contrast, closed-loop competition, which rather corresponds to a spot market, is here considered to be the equilibrium outcome "in the absence of long-term contracting."[11] On

[9] Worldwide institutions are putting increasing emphasis on environmental issues. At the EU level, environmental concerns evidently appear from the extremely rich package of documents published by the European Commission on pollution problems (as a review on this, one can visit the site http://ec.europa.eu/energy/energy_policy/documents_en.htm).

[10] Several authors have modelled open-loop Cournot games to represent imperfect competition in hydro-thermal electricity generation with natural storage of water. For the sake of illustration, Arellano [2] considers a Cournot duopoly with a competitive fringe and a mixed hydro-thermal generating portfolio, Bushnell [6] focuses on a Cournot oligopoly with a competitive fringe in which firms possess a mixture of hydro and thermal resources. Within the open-loop framework, it emerges that hydro operators can exert *static* market power (without water withdrawal) by properly choosing how much to use for production in different periods, depending upon the specific market conditions. With respect to this approach, CM push the analysis one step further. Looking at closed-loop games, they highlight that hydro operators can exert a more sophisticated form of *intertemporal* market power while competing with thermal operators. A comprehensive view of the ways hydro producers exert market power is found in Rangel [15]. The latter also discusses the main competition issues that result from strategic behaviour in electricity systems dominated by hydro generation.

[11] Murphy and Smeers [14] study investments in generation capacity in restructured electricity systems.

top of that, we accommodate for the model to capture various possible market structures. More precisely, while CM develop the analysis for the case of a single thermal producer, we allow the thermal activity to be more or less competitive, ranging from the case of a single producer to that of a competitive fringe.

Analogously to CM, we take competition to occur between producers that use two different technologies. While this is the case in countries like New Zealand, as mentioned, it is not in others, where competition takes place between producers that manage a mix of production processes. However, this does not invalidate our approach. The model we adopt, indeed, may well represent competition between generators whose technological mixes are quite asymmetric.[12] We further abstract from the possibility that nuclear technology may be used. This choice is innocent in that, for the reasons previously illustrated, our analysis would nonetheless apply to situations in which not only hydro and thermal plants but also nuclear plants are active. The message we draw is thus more general than the stylistic simplicity that our model might suggest.

Our analysis delivers two main results.

The first result pertains to the impact of long-term contracting on social welfare. We show that the welfare effects depend upon the specific pattern that consumption follows over the water cycle. More precisely, in frameworks where demand peaks at the first period of the cycle, long-term contracting enhances welfare. That is, from a social viewpoint, open-loop competition is more desirable than closed-loop competition. By contrast, in frameworks where consumption peaks at the second period after renewal of the water reserve (and demand seasonality is strong enough), long-term contracting results in a hydropower profile that yields lower welfare. That is, closed-loop competition is more desirable from a social perspective. In terms of policy, this indicates that long-term contracts are to be promoted in the former kind of situations (first-period peak) and discouraged in the latter (second-period peak).

The second result regards the impact of long-term contracting on environmental damages. We find that whether or not electricity is sold under long-term contracts it is unlikely to make a significant difference in terms of environmental quality. This follows from the observation that, "in a linear context", water transfers have *no* impact whatsoever on total thermal production, so that the intertemporal profile of hydro-production has only a second-order impact on emissions. To make the picture more precise, we further evi-

They use an open-loop Cournot game to model an oligopoly where capacity is simultaneously built and sold in long-term contracts. They rely upon a closed-loop Cournot game to represent a spot market in which investment decisions are made in the first stage and the sales decisions in the second stage.

[12] One may think about Chile, for instance. In this country, Compañía General de Electricidad, which uses natural gas to produce electricity, operates in competition with Copec, that generates electricity based on thermal resources, and Colbún, that currently generates 1274 MW of hydropower and 1236 MW of thermal power from fossil fuels. The latter is destined to become a predominantly hydro producer once the HidroAysén project to create five additional hydro plants (in joint venture with Endesa) will be completed.

dence that, when the thermal sector turns out to be structured as a competitive fringe (and, hence, environmental concerns are particularly strong), the environmental effects are critically related to the pattern of (thermal) *market shares* rather than to the pattern of *consumption*. From a policy viewpoint, it seems impossible to deliver a universal rule for the fully general case. Yet, the environmental effects of long-term contracting can be precisely assessed and we explain how to appraise them by means of simple data.

The remainder of the article is organized as follows. In Section 2, we first describe the model and then present the first- and second-best scenarios. In Section 3, we revisit the open- and closed-loop Cournot competition *à la* CM. In Section 4, we identify the impact of long-term contracting on social welfare and environmental damage. In Section 5, we provide a few policy insights.

2 The model

We adopt a discrete intertemporal model of Cournot competition in power generation. The model is similar to that of CM with the main novel aspect that environmental externalities are accounted for. The model is also revisited to accommodate for various degrees of competition.

Specifically, we suppose that electricity is produced by firms that use different technologies. One firm, that we name "firm H," runs hydropower plants. One or more firms, that we name indifferently "sector T" or "firm T" (referring to the representative thermal firm), manage thermal plants.[13] All firms schedule production over a time span of two periods ($t = 1, 2$) at zero intertemporal discount. The possibility that generation plants will be saturated is neglected.[14]

Thermal output at period t is denoted q_t^T. The variable cost associated with the production of q_t^T units is $C\left(q_t^T\right)$. The function $C(\cdot)$ is identical in the two periods. It is increasing and convex in its argument ($C_t' \equiv \partial C/\partial q_t^T > 0$, $C_t'' \equiv \partial^2 C/\partial\left(q_t^T\right)^2) \geq 0$). Sector T also incurs a fixed cost F^T. In each period, the thermal process releases polluting emissions $e\left(q_t^T\right)$, which are larger the bigger the output ($e_t' \equiv \partial e/\partial q_t^T > 0$). Emissions create an environmental damage $D\left(e\left(q_t^T\right)\right)$, with $D(\cdot)$ a smooth function increasing in the level of emissions ($D_t' \equiv \partial D\left(e\left(q_t^T\right)\right)/\partial e > 0$).

Hydropower is generated using water stored in reservoirs. The available stock of water, denoted S, is exogenously given as reservoirs are replenished naturally at the beginning of the first period. The stock is commonly known in the industry and can be used for

[13] We refer to a representative firm to model the thermal sector. Two polar cases can arise. First, this firm acts as a monopolist and we are back to the CM model. Alternatively, it behaves as a price taker and thus represents a competitive fringe facing a hydropower monopolist. Further details about the structure of the thermal sector are reported in Subsection 3.1.

[14] Capacity constraints are possibly captured by infinite costs.

production during the first and the second period.[15] One unit of water allows firm H to generate one unit of power. Thus, the firm faces the intertemporal water constraint

$$\sum_{t=1,2} q_t^H \leq S, \tag{1}$$

where q_t^H denotes the quantity of hydropower at period t. As the resource is scarce, constraint (1) holds, in fact, as an equality and no water is left at the end of period 2. In other words, no spillage occurs. To perform the activity, firm H bears a fixed cost F^H. It incurs no variable cost because the production cost associated with the hydro process does not depend on using water.[16]

Electricity is a standardized commodity so that firms offer a homogeneous good. Total utility from consumption of $Q_t = q_t^T + q_t^H$ units of power at period t is denoted $u_t(Q_t)$. The function $u_t(\cdot)$ is period-specific. It is increasing and strictly concave in its argument ($u_t' \equiv \partial u_t / \partial Q_t > 0$, $u_t'' \equiv \partial^2 u_t / \partial Q_t^2 > 0$). Environmental externalities do not affect electricity consumption. In each period, the demand for electricity is perfectly known, provided the main part of its yearly variability can be predicted with reasonable accuracy.

2.1 First best

We begin by exploring the first-best scenario. The social-welfare function is written

$$W\left(q_1^T, q_1^H, q_2^T, q_2^H\right) = \sum_{t=1,2} u_t(Q_t) - \sum_{t=1,2} C\left(q_t^T\right) - F^T - F^H - \sum_{t=1,2} D\left(e\left(q_t^T\right)\right). \tag{2}$$

Social welfare is the difference between consumer utility and social costs. The latter include the producers' production costs (*i.e.*, the private costs) and the environmental damage (*i.e.*, the external cost). The first-best profile of output is pinned down by maximizing the social-welfare function subject to (1). Suppose the first-best allocation is an interior solution.[17] Then, it satisfies the set of conditions

$$p_t = \mu = C_t' + D_t' e_t', \ t = 1, 2, \tag{3}$$

[15] In practice, water reserves are constituted in some specific periods rather than at a specific point in time *i.e.*, depending on the source of reservoirs filling, when rivers are flooding, when it rains intensely, when snow and ice melt. For the purpose of our model, the availability of the reserve over the two periods is important.

[16] In the model, only the thermal process is taken to induce externalities. This does not mean that, in practice, the hydro process has no environmental impact. Actually, it does induce soil and site deterioration. Nevertheless, unlike the thermal emissions, the external damage that is provoked by the hydro technology does not depend on the amount of produced output. Because we are interested mainly in the firms' production strategies, we can neglect the externalities induced by the hydro process.

[17] Unless otherwise specified, the focus on interior solutions will be maintained throughout the paper, although welfare maximization may actually call for corner solutions. See CM for a detailed discussion about corner solutions in an environment where externalities are not accounted for.

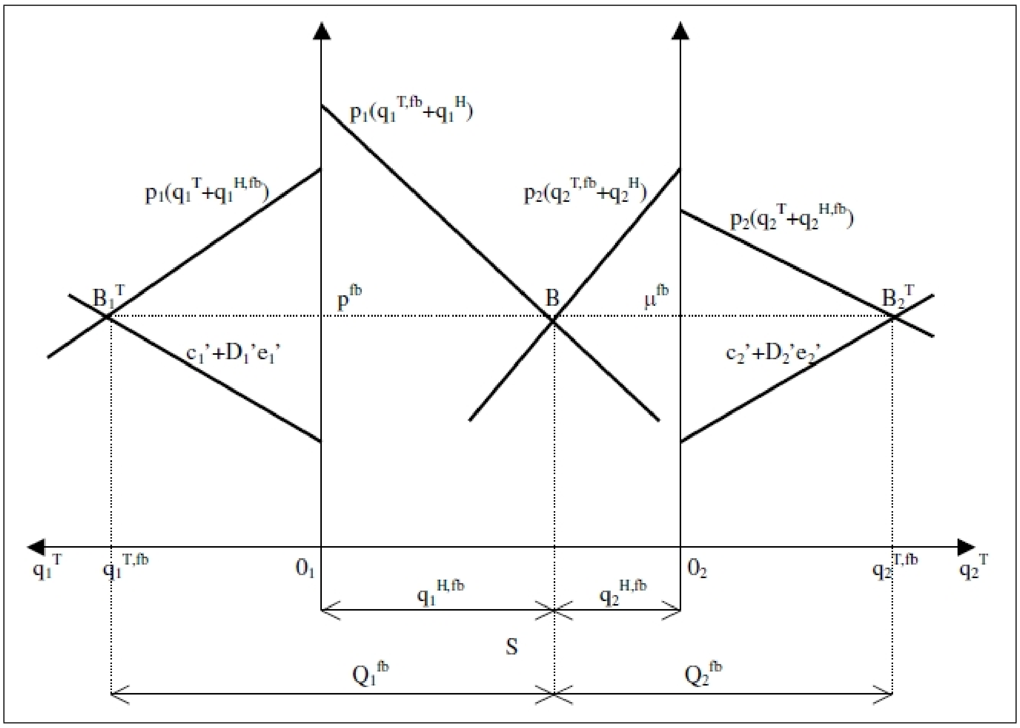

Figure 1: *The first-best output and price profiles.* The central box, which has a breadth equal to S, shows how the stock of water is allocated between period 1 (the left quadrant with origin 0_1) and period 2 (the right quadrant with origin 0_2). Given the first-best thermal output profile $(q_1^{T,fb}, q_2^{T,fb})$, the optimal water allocation $(q_1^{H,fb}, q_2^{H,fb})$ is such that the period-1 marginal utility $p_1(q_1^{T,fb} + q_1^H)$ equals the period-2 marginal utility $p_2(q_2^{T,fb} + q_2^H)$. This situation is represented by point B. The first-best thermal quantities are depicted in the extreme quadrants. In the left (resp. right) quadrant, $q_1^{T,fb}$ (resp. $q_2^{T,fb}$) is such that, given the optimal hydro output, the period-1 (resp. period-2) marginal utility $p_1(q_1^T + q_1^{H,fb})$ (resp. $p_2(q_2^T + q_2^{H,fb})$) equals the period-1 (resp. period-2) social marginal cost $c_1' + D_1'e_1'$ (resp. $c_2' + D_2'e_2'$). This situation is identified by point B_1^T (resp. B_2^T). Points B, B_1^T and B_2^T altogether identify the first-best price $p^{fb} \equiv p_1(q_1^{T,fb} + q_1^{H,fb}) = p_2(q_2^{T,fb} + q_2^{H,fb})$. The latter equals the shadow cost of water as well as the social thermal marginal cost in either period.

where μ is the Lagrange multiplier associated with the resource constraint, which represents the shadow cost of water. Equation (3) says that, at social optimum, electricity should be equally priced over time. In each period, the energy price should equal the shadow cost of water as well as the social marginal cost of the thermal output. Because the cost, the damage and the emission functions are identical in the two periods, sector T should generate the same amount of power at $t = 1, 2$. Observe that the demand varies from one period to the other. The hydro producer should thus compensate for these variations, thereby perfectly smoothing the thermal output profile.

A graphical illustration of the profile of first-best prices and quantities, as characterized by condition (3), is provided in Figure 1. This and the subsequent graphs (except for that in Figure 5) are constructed supposing that period 1 is the peak period (*i.e.*, the period in which demand is higher) and period 2 the off-peak period (*i.e.*, the period in which demand is lower). In all figures, the relevant functions are drawn as linear for purely graphical convenience: the linear stylization does not change the main content of the graphs.

2.2 Second best

At first best, producers may not be able to balance the budget. To account for producers' financial concerns, we now investigate a second-best framework.

In principle, in our setting, budget balance could be an issue for any producer, depending upon the relative size of fixed costs. In practice, in electricity markets, production technologies are such that marginal and fixed costs are inversely related. Typically, in the thermal process, the marginal cost is large and the fixed cost relatively small. In the hydro process, instead, the fixed cost is large and the marginal cost (nearly) zero. This suggests that the hydro producer would be more likely to incur financial difficulties at first best. We thus focus on this case in the sequel of the analysis. It is, however, noteworthy that we would obtain qualitatively similar results if we consider a situation in which the thermal sector were exposed to losses at first best.

The second-best allocation is pinned down by maximizing (2) subject to (1) and to the constraint

$$\pi^H\left(q_1^H, q_2^H; q_1^T, q_2^T\right) = \sum_{t=1,2} q_t^H p_t\left(Q_t\right) - F^H \geq 0, \tag{4}$$

which ensures that the profit be non-negative for firm H. Let λ^H be the Lagrange multiplier associated with (4). The second-best quantity pair is characterized by the set of conditions

$$\frac{p_t - \left(C_t' + D_t' e_t'\right)}{p_t} = \lambda^H \frac{s_t^H}{\varepsilon_t\left(Q_t\right)}, \quad t = 1, 2 \tag{5a}$$

$$\frac{p_t - \widetilde{\mu}}{p_t} = \frac{\lambda^H}{1+\lambda^H} \frac{s_t^H}{\varepsilon_t\left(Q_t\right)}, \quad t = 1, 2, \tag{5b}$$

where $s_t^H \equiv q_t^H / Q_t$ is the market share of the hydro producer in period t, $\varepsilon_t\left(Q_t\right) \equiv -p_t / p_t' Q_t$, with $p_t' \equiv \partial p_t / \partial Q_t$, is the (absolute value of the) price elasticity of market demand in period t and $\widetilde{\mu} \equiv \mu / \left(1+\lambda^H\right)$ is a deflated measure of the shadow cost of water. Condition (5a) reveals that, at second best, the price exceeds the *social* marginal cost of the thermal activity in either period. Indeed, for firm H to break even, sector T should obtain a larger-than-first-best per-period markup. Condition (5b) shows that the price also exceeds the deflated shadow cost of water in either period. Specifically, the price obeys a rule that is similar to the monopoly Ramsey rule. According to (5b), how much the general price level is above first best depends upon the size of F^H, which is reflected in the ratio $\lambda^H / \left(1+\lambda^H\right)$. On the other hand, the specific price level in each period depends on the demand elasticity as well as on the market share of the hydro

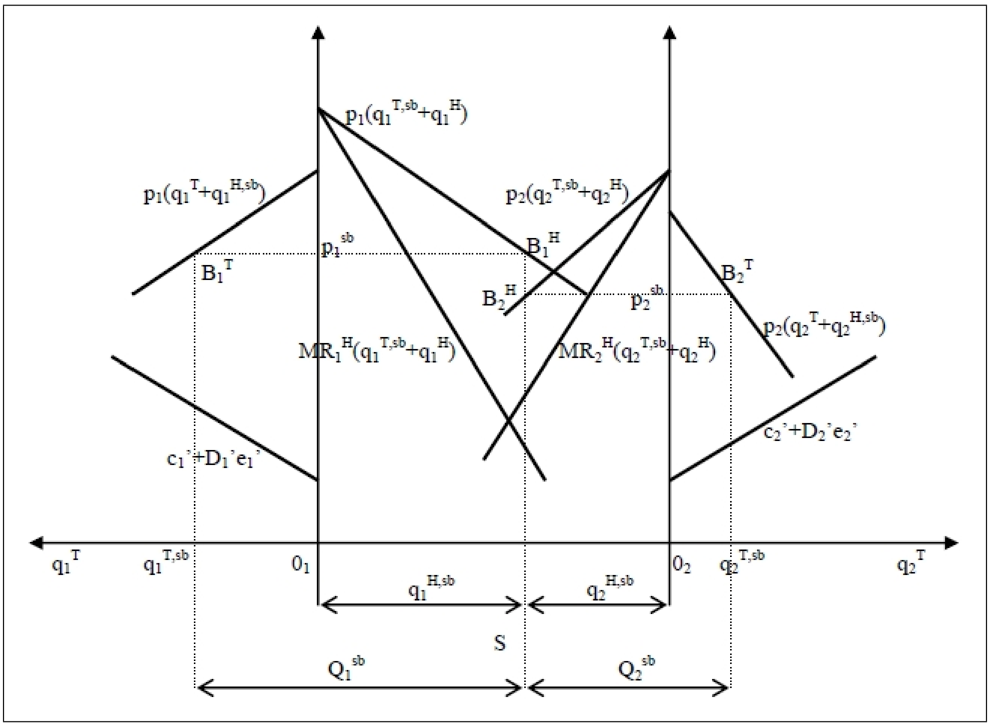

Figure 2: *The second-best output and price profiles.* Given the second-best thermal-output profile $(q_1^{T,sb}, q_2^{T,sb})$, the second-best water allocation $(q_1^{H,sb}, q_2^{H,sb})$ is such that the period-1 marginal revenue $MR_1^H(q_1^{T,sb}+q_1^H)$ from hydro production is smaller than the period-2 marginal revenue $MR_2^H(q_2^{T,sb}+q_2^H)$. The second-best equilibria for firm H are identified by points B_1^H and B_2^H in the central box. The second-best equilibria for firm T are depicted in the extreme quadrants. In the left (resp. right) quadrant, $q_1^{T,sb}$ (resp. $q_2^{T,sb}$) is such that, given the second-best hydro output, the period-1 (resp. period-2) marginal utility $p_1(q_1^T + q_1^{H,sb})$ (resp. $p_2(q_2^T + q_2^{H,sb})$) is larger than the period-1 (resp. period-2) social marginal cost $c_1' + D_1'e_1'$ (resp. $c_2' + D_2'e_2'$). The corresponding equilibrium is identified by point B_1^T (resp. B_2^T). The price raise above the first-best level is more important in the peak period $(t = 1)$, so that the period-1 second-best price $p_1^{sb} \equiv p_1(q_1^{T,sb} + q_1^{H,sb})$ is higher than the period-2 price $p_2^{sb} \equiv p_2(q_2^{T,sb} + q_2^{H,sb})$.

producer. That is, *ceteris paribus*, the price is higher in the period in which the market demand is less elastic. Moreover, to facilitate break-even, it is optimal that firm H sells relatively more when the price is higher. A graphical illustration of the profile of second-best prices and quantities, as characterized by conditions (5a) and (5b), is provided in Figure 2.

Combining (5a) and (5b) yields

$$p_1 - p_2 = \frac{\lambda^H}{1+\lambda^H}\left(p_2' q_2^H - p_1' q_1^H\right) \tag{6a}$$

together with

$$p_1 - p_2 = \frac{1}{\lambda^H}\left[(C_1' + D_1' e_1') - (C_2' + D_2' e_2')\right]. \tag{6b}$$

Condition (6a) shows that, *ceteris paribus*, the wedge between the second-best prices should be larger the tighter the budget constraint of firm H. However, condition (6b) further suggests that the divergence in prices comes along with a divergence in social marginal costs. This means that social costs are not minimized. To contain this efficiency loss, the price difference is to be kept as small as possible by raising both prices.[18] Noticeably, this distortion can be completely avoided when the cost, the damage and the emission functions are all linear in quantity. In that case, at second best, the price is raised above the first-best level exactly by the same amount in the two periods.

3 Cournot competition

We now concentrate on the situation in which firms compete *à la* Cournot. As firms do not take externalities into account, the equilibrium strategies in the Cournot duopoly are essentially those described by CM. In what follows, we revisit their analysis to allow for various degrees of market competition. We begin by presenting the open-loop game, in which firms maximize profits statically. This game mirrors an institutional setting in which output is sold under *long-term contracts*. We then consider the closed-loop game, in which the hydro producer takes advantage of its ability to commit to a given output profile so as to internalize the effects of its current decisions on future performance. We interpret this setting, which is more similar to spot markets, as the *equilibrium outcome in the absence of long-term contracts*.

3.1 The open-loop game

Before analyzing the open-loop game (*i.e.,* competition under long-term contracting), we find it useful to look more deeply into the composition of the thermal sector, which we have only briefly presented within the model description. This allows us to illustrate in greater details how the analysis of CM is extended to accommodate for market structures other than the hydro-thermal duopoly they consider.

Sector T (also denominated "firm T" with reference to the representative thermal firm) includes $n \in \mathbb{N}$ producers competing *à la* Cournot. For simplicity, assume that each producer supplies the quantity $q_t = q_t^T/n$ and bears the (private) variable cost $c(q_t) = C(q_t^T)/n$ in each period t. It also incurs the fixed cost $f = F^T/n$. When $n = 1$, the market is structured just as in the CM duopoly, in which firm H competes with a single thermal firm. As n grows very large, the thermal sector becomes a competitive fringe of price-taking producers. Each producer in sector T takes the production decisions

[18] An intertemporal divergence arises also at first best when the efficient allocation is not an interior solution. In that case, it would be optimal to use the water stock entirely in one period. At first best, a corner allocation of the kind $q_t^H = S$ and $q_z^H = 0$, $q_t^T = 0$ and $q_z^T > 0$ arises whenever $\mu < c_t'(0) + D_t' e_t'(0)$. This says that, as long as the shadow cost of water is smaller than the social marginal cost of the thermal output at $q_t^T = 0$, the water reserve should be exhausted at period t and the thermal process should run only at period $z \neq t$.

of the other firms as given and chooses output q_t, $t = 1, 2$, so as to maximize its profit function

$$\pi(q_t, \widetilde{Q}_t) = \sum_{t=1,2} q_t p_t(q_t + \widetilde{Q}_t) - \sum_{t=1,2} c\,(q_t) - f,$$

where $\widetilde{Q}_t = q_t^H + (n-1)\,q_t$ denotes the quantity that is provided, in total, by all the (hydro and thermal) competitors. For each thermal producer, the best response function is written $p_t + q_t p_t'(q_t + \widetilde{Q}_t) - c_t'\,(q_t)$. Thus, the optimal production rule of the representative firm T is given by

$$p_t + \alpha q_t^T p_t' = C_t', \;\; t = 1, 2, \tag{7}$$

where $\alpha = 1/n$ is to be interpreted as a measure of the degree of competition in the thermal sector. Clearly, in each period, the price exceeds the marginal cost as long as $\alpha > 0$, in which case firm T obtains a positive markup. By contrast, the price is equal to the marginal cost when sector T is a competitive fringe.

The equilibrium price depends on the market demand, so that it does not need to be constant over time. Recall that, by contrast, the first-best price reflects only the (social) costs, hence it is constant across periods. Yet, it exceeds the per-period private marginal cost, thereby contributing to incorporating the externality indirectly. This evidences that having the thermal producer exert market power, contributes to alleviating environmental problems.

Firm H also takes the production decisions of firm T as given and chooses quantity q_t^H, $t = 1, 2$, so as to maximize the profit function in (4) subject to (1). From the first-order condition with respect to the per-period hydro output, one obtains

$$p_1 + q_1^H p_1' = p_2 + q_2^H p_2' = \mu. \tag{8}$$

Firm H allocates the available water so that marginal revenues are equal across periods and equal to the shadow cost of water. Condition (8) identifies the intertemporal profile of hydropower for any given profile of thermal output. It shows that, at the open-loop equilibrium, the price exceeds the shadow cost of water at each t. This reflects the benefits that firm H obtains, at the margin, in the two periods. From CM we know that a hydro monopolist allocates water over time so that the peak price is *above* the first-best level whereas the off-peak price is *below*. This intertemporal distortion follows from the circumstance that water is available in a limited amount.[19] In a hydro-thermal

[19] Were a large amount of water available, the hydro producer could drive the price *above* the first-best level in either period by withdrawing some water from production. To avoid strategic withdrawal, free disposal is legally banned, in general, in countries where water reserves are copious and hydropower largely predominates. In addition, public authorities make an effort to solicit and diffuse information on reservoir-filling. For instance, in Norway, starting from December 2002, the Water Resources and Energy Directorate began to provide more detailed information, as compared to the past, about reservoirs filling in the country. In particular, information about aggregate reservoir levels for four different regions

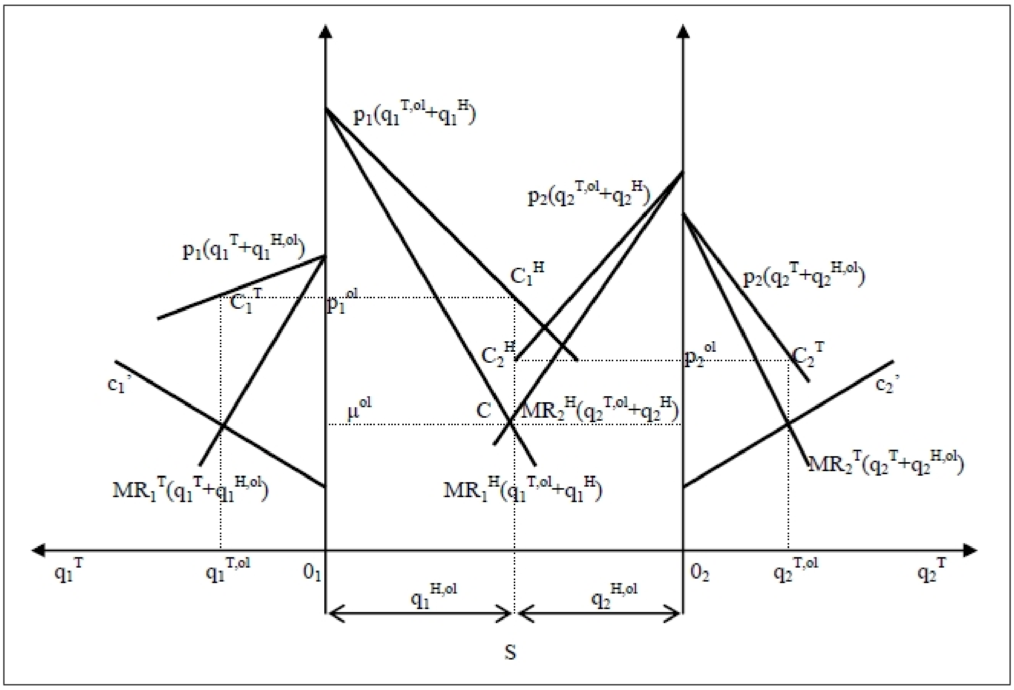

Figure 3: *The equilibrium with long-term contracts (the open-loop game).* Given the open-loop thermal output profile $(q_1^{T,ol}, q_2^{T,ol})$, the water reserve is allocated so that the period-1 marginal revenue $MR_1^H(q_1^{T,ol} + q_1^H)$ from hydro production is equal to the period-2 marginal revenue $MR_2^H(q_2^{T,ol} + q_2^H)$. This situation is represented by point C, which identifies the pair of open-loop hydro quantities $(q_1^{H,ol}, q_2^{H,ol})$. Points C_1^H and C_2^H represent the open-loop equilibria for firm H in periods 1 and 2, respectively. The open-loop equilibria for firm T are depicted in the extreme quadrants. In the left quadrant, $q_1^{T,ol}$ (resp. $q_2^{T,ol}$) is such that, given the open-loop hydro output, the period-1 (resp. period-2) marginal revenue $MR_1^T(q_1^T + q_1^{H,ol})$ (resp. $MR_2^T(q_2^T + q_2^{H,ol})$) from thermal production is equal to the private marginal cost c_1' (resp. c_2'). The corresponding equilibrium is represented by point C_1^T (resp. C_2^T). The shadow cost of water μ^{ol} is equal to the hydro marginal revenue in either period. The open-loop period-1 price $p_1^{ol} \equiv p_1(q_1^{T,ol} + q_1^{H,ol})$ is larger than the open-loop period-2 price $p_2^{ol} \equiv p_2(q_2^{T,ol} + q_2^{H,ol})$, *i.e.*, the price attains a higher level in the peak period $(t = 1)$.

oligopoly, the hydro producer is a monopolist *vis-à-vis* the demand that is not served by the thermal competitors. For a given thermal output profile, water is allocated so as to create enough shortage and raise scarcity rents in the peak period. The equilibrium of the open-loop game is graphically illustrated in Figure 3.

3.2 The closed-loop game

Recall that, in the kind of situations we consider, water withdrawal does not occur *i.e.*, the hydro producer devotes the entire stock of resource to power generation. Actually, in such situations, once some hydro output is produced in period 1, the hydro output to be produced in period 2 is just what is left out of the water reserve $\left(q_2^H = \left(S - q_1^H\right)\right)$. This circumstance provides a natural commitment device to firm H, which can thus act as a

replaced information about aggregate reservoir levels for Norway as a whole (Grønli and Costa [8]). By contrast, if water is scarce enough, water withdrawal is spontaneously avoided, as it would not be profitable.

"Stackelberg leader" *vis-à-vis* the thermal competitors. When this occurs, a closed-loop Cournot game unfolds. As already mentioned, the outcome of this game can be viewed as the market outcome in the absence of long-term contracts.

Under closed-loop competition, the quantity profile of firm T still obeys the profit-maximizing rule in (7). As for firm H, profit maximization now yields

$$\begin{aligned} p_1 + q_1^H p_1' &= p_2 + q_2^H p_2' \left(1 + Q_2^{T\prime}\right) \\ &= p_2 + q_2^H p_2' Q_2', \end{aligned} \tag{9}$$

where $Q_2^{T\prime} \equiv \left(dQ_2^T / dq_2^H\right)$ and $Q_2' \equiv \left(dQ_2 / dq_2^H\right)$. Condition (9), which follows from $\left(-dq_2^H / dq_1^H\right) = 1$, dictates the equality between the "relevant" marginal revenues in period 1 and 2. In the open-loop game, firm H computes the period-2 marginal revenue taking q_2^T as exogenously given. In the closed-loop framework, it anticipates how the choice of q_1^H (and so of q_2^H) will affect that of q_2^T. Specifically, firm H forecasts that any increase in the hydro supply at period 2 will be partially compensated by a decrease in the thermal supply. Thus, for any given thermal output profile, it now allocates more water to period 2. It thus exerts a subtle form of *intertemporal market power*, as evidenced by CM. At the closed-loop equilibrium, one has

$$p_1 + q_1^H p_1' > p_2 + q_2^H p_2'.$$

This inequality shows that the marginal revenue of firm H in period 1 exceeds the marginal revenue that firm H would get in period 2 in an open-loop game. Remarkably, *ceteris paribus*, the hydro producer is better off at the closed-loop equilibrium because, by accounting for time irreversibility, it is able to take better advantage of the divergence in per-period market conditions. A graphical illustration of the equilibrium of the closed-loop game is provided in Figure 4.

One might find the outcomes previously described, at odds with the functioning of a real-world power generation market, or at least perceive them as a naive view of it. Indeed, given the costs structure, hydro producers usually have priority over thermal producers in the merit order of a deregulated market. One might thus quickly conclude that they will use this advantage to smooth their output profile, leaving to the thermal competitors the sole residual demand and the burden to adjust production to demand fluctuations. Our analysis evidences that, in fact, a firm that manages a limited water reserve, stored at no cost, can do better than simply smoothing its production schedule. The adoption of a more profitable (although time-varying) production profile is made possible precisely because the hydro producer can (i) freely store the resource and (ii) release it at any time thanks to the priority it receives in the merit order.

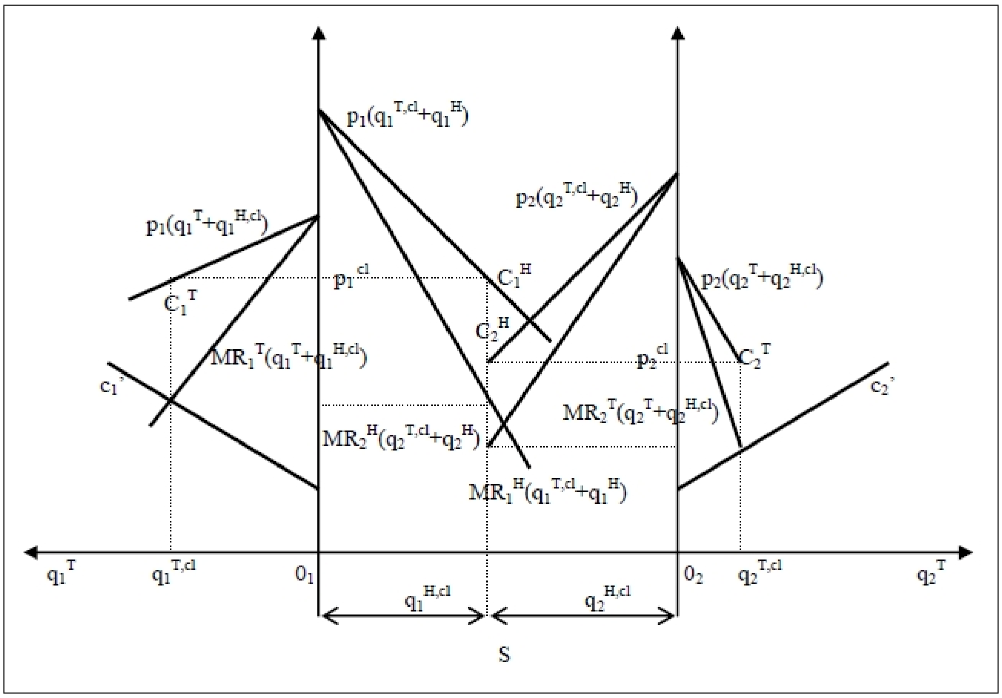

Figure 4: *The equilibrium in the absence of long-term contracts (the closed-loop game).* The closed-loop hydropower profile $(q_1^{H,cl}, q_2^{H,cl})$ is such that, given the closed-loop thermal output profile $(q_1^{T,cl}, q_2^{T,cl})$, the period-1 marginal revenue $MR_1^H(q_1^{T,cl} + q_1^H)$ from hydro production is *larger* than the period-2 marginal revenue $MR_2^H(q_2^{T,cl} + q_2^H)$. This reflects the circumstance that firm H internalizes the effects of its current decisions on future performance.

4 Long-term contracting, social welfare and environmental externalities

We have seen that the hydro producer can raise its profit by transferring water strategically over time. In particular, absent long-term contracting (*i.e.,* under closed-loop competition), firm H produces less in period 1 and more in period 2. This raises two main questions. First, how does long-term contracting impact social welfare? Second, how does it affect environmental problems?

Replying to these questions requires that we assess whether open-loop competition is more or less desirable than closed-loop competition in terms of both social welfare and environmental quality. However, providing a precise answer is far from obvious as it depends, *a priori*, on all the relevant markets and technological characteristics. Despite this difficulty, it is possible to develop general insights by considering specific (and polar) cases.

To reply to the first question, we explore a linear framework in which intertemporal water transfer has *no* impact on environmental damage. This circumstance enables us to highlight the impact of long-term contracting on social welfare *net of the environmental externality.*

To reply to the second question, we come back to a general setting and look at the polar case in which the hydro producer faces a competitive thermal fringe $(\alpha = 0)$. This approach is useful in that *environmental problems are exacerbated* in the absence of market power on the thermal side. In this case, we derive a very simply rule to decide whether long-term contracting would lead to an improvement or, conversely, to a deterioration of environmental health.

4.1 The impact of long-term contracting on social welfare

Observe first that water transfers are likely to have only a second-order impact on environmental health. More precisely, if the inverse demand curve and the thermal marginal cost in period $t = 1, 2$ are respectively written

$$p_t(Q_t) = A_t - BQ_t \quad \text{and} \quad C_t'\left(q_t^T\right) = C_A + C_B q_t^T, \tag{10}$$

then the intertemporal allocation of water does *not* affect the total thermal production $Q^T = \sum_{t=1}^{2} q_t^T$. The decrease in thermal production that is induced by an increase in hydropower supply in one period is exactly offset by the associated increase in thermal production in the other period.[20] In other words, as long as (10) holds true, environmental damages only depend upon Q^T, hence they are *not* affected by strategic water transfers. Note that this holds true whatever the degree of market competition in the thermal sector (it does not depend upon α). Thus, it is fair to say that long-term contracting has *no* first-order impact on environmental damages.

Of course, there is no reason for which demand and supply should be linear. Yet, by restricting our analysis to the setting here introduced, we can isolate the effects of water transfers (and hence of long-term contracting) on price distortions.

The impact of strategic water allocation is critically related to the market characteristics. More precisely, it depends on whether demand peaks at the first or the second period of the water cycle.[21] Given the behaviour of the thermal producers, the socially optimal allocation of water would be such that the electricity price is constant over time.

[20] All mathematical details related to this Subsection are relegated to Appendix A.

[21] Demand peaks at the first period of the water cycle in regions where the water reserve is formed in spring and early summer and demand peaks in summer. For instance, in California demand is highest over the summer period (June through September), when high temperatures trigger over-use of air conditioners and other coolants (for yearly figures about power demand in California, compare the California Energy Commission Reports and Outlooks available at http://energyarchive.ca.gov/). Demand peaks at the second period of the water cycle in countries where the water reserve is formed mainly in spring, when snow and ice melt, and is used extensively in fall and winter, essentially for heating purposes. An example is found in the Scandinavian countries (compare Grønli and Costa [8]). Similarly, customers in the U.S. Pacific Northwest use more electricity in winter than in summer. Nevertheless, the Columbia River (the largest river in the Pacific Northwest) is driven by snowmelt, with high runoff in late spring and early summer (about 60% of the natural runoff in the basin occurs during May, June and July; compare Bonneville Power Administration [5]).

Whether under open- or closed-loop competition, seeking profits induces the hydro producer to supply a sub-optimally low quantity in the peak period so as to raise the marginal revenue. On top of that, in the closed-loop game, the hydro producer tends to use less water in the first period and more in the second. Hence, the above distortion is exacerbated if demand peaks in the first period, and it is lessened if demand peaks in the second period.

To illustrate this point and to derive precise policy implications, we take the ratio $\gamma \equiv (A_1 - A_2)/2B$ to measure "demand seasonality."[22] Demand peaks at the first period when $\gamma > 0$. It peaks at the second period in the converse case. If γ is close to zero, then there is almost no seasonal pattern. If (the absolute value of) γ exceeds $S/2$, then seasonality is so important that it would be socially optimal to allocate the entire reserve of water to a single period. This is, however, an extreme case that we have neglected throughout the analysis. We also let $q_1^{H,*}$ denote the hydropower supply in period 1, when the intertemporal profile of hydro production is chosen to attain the highest level of social welfare, given that firm T maximizes its profit. Similarly, we let $q_1^{H,ol}$ and $q_1^{H,cl}$ denote the hydropower supply in period 1, respectively in the open-loop game and in the closed-loop game.

Depending upon the specific value that γ takes within the relevant interval $\left[-\frac{S}{2}, \frac{S}{2}\right]$, two different regimes can arise, one in which open-loop competition (*i.e.,* long-term contracting) dominates (*i.e.,* yields higher welfare than) closed-loop competition and the other in which the converse occurs.

The first regime arises when $\gamma \in \left(-\widetilde{\gamma}, \frac{S}{2}\right]$, where

$$\widetilde{\gamma} \equiv \frac{S}{2} \frac{B\left[2(\alpha B + C_B) + B\right]}{(\alpha B + C_B)\left[8(\alpha B + C_B) + 9B\right] + 2B^2}.$$

This says that demand either peaks at the first period of the water cycle or it peaks at the second period, but in a context of weak seasonality ($|\gamma|$ small). Under these circumstances, hydro quantities in period 1 are ranked as $q_1^{H,cl} < q_1^{H,ol} < q_1^{H,*}$ if the peak is registered in that same period ($\gamma > 0$). They are ranked as $q_1^{H,cl} < q_1^{H,*} < q_1^{H,ol}$ if demand peaks at the second period ($-\widetilde{\gamma} < \gamma < 0$). The former ranking is represented in the upper-right quadrant of the graph in Figure 5, the latter in the area immediately below the horizontal axis. In either case, welfare levels are ordered as follows:

$$W(q_1^{H,cl}) < W(q_1^{H,ol}) < W(q_1^{H,*}).$$

These inequalities show that the intertemporal water allocation in the closed-loop game

[22] Observe that $A_t/2B$ would be the equilibrium consumption in period t if the provider were a monopolist producing at zero marginal cost. The coefficient γ is thus the difference between the monopoly "virtual" consumption levels in the two periods of the water cycle.

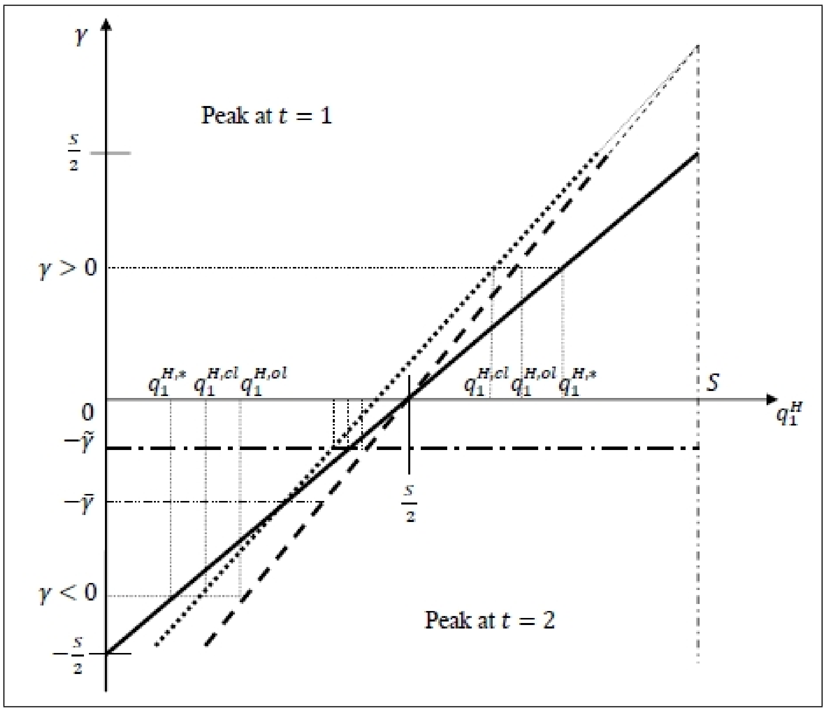

Figure 5: *Demand seasonality and hydropower quantities.* The graph shows how q_1^H (measured on the horizontal axis) varies as γ (measured on the vertical axis) varies on the relevant range $\left[-\frac{S}{2}, \frac{S}{2}\right]$. The thick, the dashed and the dotted lines represent the functions $q_1^{H,*}(\gamma)$, $q_1^{H,ol}(\gamma)$ and $q_1^{H,cl}(\gamma)$, respectively. Hydro quantities are ranked as $q_1^{H,cl}(\gamma) < q_1^{H,ol}(\gamma) < q_1^{H,*}(\gamma)$ for $\gamma > 0$ (first-period peak). They are ranked as $q_1^{H,cl}(\gamma) < q_1^{H,*}(\gamma) < q_1^{H,ol}(\gamma)$ for $\gamma \in (-\overline{\gamma}, 0)$ (weak second-period peak) and as $q_1^{H,*}(\gamma) < q_1^{H,cl}(\gamma) < q_1^{H,ol}(\gamma)$ for $\gamma \in \left[-\frac{S}{2}, -\overline{\gamma}\right)$ (strong second-period peak). Long-term contracts welfare-dominate for $\gamma \in \left(-\widetilde{\gamma}, \frac{S}{2}\right]$.

results in a lower level of welfare, as compared to the open-loop game. Therefore, when demand peaks at the first period of the water cycle (or when it peaks at the second period but the seasonal pattern is weak), long-term contracts would enhance social welfare.

The second possible regime arises whenever $\gamma \in \left[-\frac{S}{2}, -\widetilde{\gamma}\right)$. This says that demand peaks at the second period of the water cycle in a context of significant seasonality ($|\gamma|$ large). In this case, hydro quantities in period 1 are ordered as $q_1^{H,cl} < q_1^{H,*} < q_1^{H,ol}$ when seasonality is still "relatively weak." They are ordered as $q_1^{H,*} < q_1^{H,cl} < q_1^{H,ol}$ as seasonality becomes "sufficiently strong." These rankings are represented in the bottom-left area of the graph in Figure 5, the former for $\gamma \in (-\overline{\gamma}, -\widetilde{\gamma})$, with $\overline{\gamma} \equiv BS/\left[4(\alpha B + C_B) + 2B\right]$, the latter for $\gamma \in \left[-\frac{S}{2}, -\overline{\gamma}\right)$. They are both associated with the following order of welfare levels:

$$W(q_1^{H,ol}) < W(q_1^{H,cl}) < W(q_1^{H,*}).$$

These inequalities show that closed-loop competition yields a higher level of social welfare than does open-loop competition. One can thus conclude that, as long as demand peaks at the second period of the water cycle (and seasonality is "strong enough" *i.e.*, $\gamma < -\widetilde{\gamma}$), the introduction of long-term contracts would actually lower social welfare.

The analysis developed so far shows that seasonality is policy-relevant when demand peaks at $t = 2$, whereas it is not when demand peaks at $t = 1$. The reason for this is to be found in the strategic structure of the closed-loop game. In the latter, *by comparison with the open-loop game*, firm H transfers some water from period 1 to period 2, as to induce its thermal competitor(s) to reduce production in period 2. This contributes to exacerbating scarcity problems in period 1, and to alleviating them in period 2. Therefore, when demand peaks at period 1, a shift from open-loop competition to closed-loop competition unambiguously exacerbates the scarcity problem in that period. By contrast, when demand peaks at period 2, the same shift alleviates the scarcity problem in that period. However, if seasonality is weak, then the scarcity problem is likely to be of little importance. Thus, in the shift to closed-loop competition (*i.e.,* when renouncing long-term contracts), the benefits attached to the scarcity reduction in period 2 may actually be lower than the costs induced by the scarcity raise in period 1.

One last point is worth noting. The insights we have drawn from the analysis are valid whatever the degree of competition in the thermal sector. Indeed, as previously pointed out, the absence of environmental impact within the linear framework is not related to the specific market structure. The fact that the hydro producer tends to supply a sub-optimally low quantity in the peak period, is also very general and independent of α. The same holds true for the comparison between the closed-loop and the open-loop intertemporal output profile. Nonetheless, the magnitude of the phenomena under scrutiny *does depend* upon the market structure. In particular, when the thermal producers are not endowed with market power and thus act as price-takers ($\alpha = 0$), they do not account for the impact that a transfer of water to period 2 will have on the period-2 marginal revenue. Hence, *ceteris paribus*, they contract their production less than they would if they were to behave strategically. In the closed-loop game, this induces firm H to keep more water in the first period and there is less of a difference between the open and the closed-loop outcome. It also follows that the degree of seasonality $\widetilde{\gamma}$ at which the switch from the first to the second regime occurs, is closer to zero when the hydro producer faces a competitive thermal fringe than it is when the hydro producer faces a unique thermal competitor $(\alpha = 1)$. In other words, the less the thermal sector is competitive, the larger the set of circumstances under which long-term contracting appears to enhance social welfare.

4.2 The impact of long-term contracting on environmental damage

We shall now explore how the strategic behaviour of the hydro producer (*i.e.,* whether or not output is sold under long-term contracts) affects environmental problems. To this aim, we need to come back to a general setting, in which both welfare and environmental effects appear. In this framework, one can identify a precise condition under which total damage is increased, as water is transferred from period 1 to period 2, by computing the marginal impact of water transfers on thermal production (see Appendix B). One can thus identify the precise conditions under which the introduction of long-term contracts leads to a reduction in environmental damages.

As far as the fully general case is considered, the aforementioned condition is so intricate that it does not provide much intuition, and remains of scarce practical guidance. In a recent study, however, Billette de Villemeur and Pineau [4] show that this condition takes a particularly simple form when the hydro producer faces a competitive thermal fringe. In this situation, environmental problems are especially strong as thermal firms do not contract output as to exert market power. Arguably, given that the effect of strategic water transfers on emissions are likely to be of a second order, this is the only situation in which the environmental impact of long-term contracting is to be accounted for.

Specifically, when $\alpha = 0$, total damage is increased as water is transferred from period 1 to period 2 if and only if

$$\frac{D_2' e_2'}{D_1' e_1'} \frac{s_2^T}{s_1^T} < \frac{\varepsilon_2/\eta_2}{\varepsilon_1/\eta_1}, \tag{11}$$

where $s_t^T \equiv q_t^T/Q_t$ denotes the thermal market share and $\eta_t \equiv \left(p_t/q_t^T\right)\left(dq_t^T/dp_t\right) = p_t/C_t'' q_t^T$ denotes the elasticity of the (competitive) thermal supply in period $t = 1, 2$. Assuming that both polluting emissions and environmental damages are proportional to thermal output so that the marginal damage is constant and identical in the two periods ($D_1' e_1' = D_2' e_2'$), this further reduces to

$$\frac{s_2^T}{s_1^T} < \frac{\varepsilon_2/\eta_2}{\varepsilon_1/\eta_1}. \tag{12}$$

This says that long-term contracting (less water transferred from period 1 to period 2) is beneficial to the environment whenever the ratio of thermal market shares $\left(s_2^T/s_1^T\right)$ is "sufficiently low."

Whether condition (11) holds true is, in our opinion, mainly an empirical question. In fact, the pattern of market shares has no obvious link with that of equilibrium prices (or consumption). More precisely, one can easily establish that:

$$Q_t^2 \frac{ds_t^T}{dp_t} = \frac{dq_t^T}{dp_t} q_t^H - q_t^T \frac{dq_t^H}{dp_t}.$$

Arguably, when demand peaks, prices are higher and both hydro and thermal producers tend to supply more in that period. If the water reserve is sufficiently large, so that $q_t^H \left(dq_t^T/dp_t\right) > q_t^T \left(dq_t^H/dp_t\right)$, then the pattern of thermal market shares tends to follow the price (or demand) pattern. Conversely, if the water reserve is relatively scarce, then thermal market shares tend to display an opposite pattern as compared to prices.

The associated heuristic is that, *ceteris paribus,* when water is relatively abundant, both price distortions and environmental damages are likely to be reduced by long-term contracting in situations in which consumption peaks in the first period rather than in the second period of the water cycle. By contrast, when water is relatively scarce (and thus external costs potentially greater), price distortions and environmental damages move in opposite directions. That is, an intertemporal water transfer that exacerbates price distortions lessens environmental damages and *vice versa*. Given that environmental effects are likely to be second-order ones, we believe that, in this latter case, the sole price distortions should be considered to appraise the opportunity of resorting to long-term contracts.

5 Concluding remarks

Two main insights can be drawn from our analysis.

First, in hydro-thermal electricity markets where hydro producers manage a scarce water reserve that is naturally renewed over time, the adoption of long-term contracts can have either a negative or a positive effect on social welfare, depending upon the intertemporal consumption pattern over the water cycle. Specifically, our results suggest that, when demand displays significant seasonality, long-term contracts tend to reinforce price distortions (*i.e.,* closed-loop competition welfare-dominates open-loop competition) as long as consumption peaks at the second period of the water cycle. On the other hand, long-term contracts attenuate price distortions (*i.e.,* open-loop competition welfare-dominates closed-loop competition) whenever consumption peaks at the first period. In terms of policy, this points to the conclusion that long-term contracting should be deterred in the former case and promoted in the latter.

The second insight is that long-term contracts are likely to have a minor impact on environmental quality, since strategic water transfers have only a second-order effect on total thermal output. This result evidences that the exercise of intertemporal market power by hydro producers is not comparable to the exercise of "standard" market power that, rather, induces a first-order effect. Neither does it work as a simple tax, which would also have a first-order impact. Because environmental health does not depend critically on the adoption of long-term contracts, pollution control in hydro-thermal electricity sectors does not seem to be crucial for deciding whether or not to rely on the latter. This also makes the difficulty less relevant in identifying simple and universal guidelines for assessing the environmental effects of long-term contracting. Notwithstanding, our study does provide a practical recipe for appraising the marginal environmental impact in a case in which pollution issues are exacerbated, namely when the thermal sector is a perfectly competitive fringe. Specifically, this requires the use of data about the intertemporal pattern of (thermal) market *shares* over the water cycle.

We limit ourselves to study how the adoption of long-term contracts affects the outcome of hydro-thermal electricity markets. An open question is how to design appropriate corrective interventions in order to decentralize the *optimal* intertemporal hydropower profile. This question is on our research agenda.

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A The impact of long-term contracting on social welfare

Suppose that, in period $t = 1, 2$, the inverse demand curve is written

$$p_t(Q_t) = A_t - BQ_t.$$

By definition $p_t = U_t'(Q_t)$ so that

$$U_t(Q_t) = \left(A_t - \frac{1}{2}BQ_t\right)Q_t.$$

Further suppose that the total thermal cost function is given by

$$C\left(q_t^T\right) = \left(C_A + \frac{1}{2}C_B q_t^T\right)q_t^T + F^T.$$

Finally, suppose that the damage function is given by

$$D\left(e\left(q_t^T\right)\right) = Dq_t^T.$$

A.1 The thermal best reply

Under Cournot competition, the best-reply function of the representative thermal firm is written

$$p_t(Q_t) + \alpha p_t' q_t^T = C'\left(q_t^T\right).$$

Hence, in the particular framework here considered, it specifies as

$$A_t - Bq_t^H - (1+\alpha)\, Bq_t^T = C_A + C_B q_t^T.$$

This yields the profit-maximizing thermal quantity

$$q_t^T = \frac{A_t - C_A - Bq_t^H}{(1+\alpha)\, B + C_B}.$$

As a result, the market quantity in period t is found to be

$$Q_t\left(q_t^H\right) = q_t^H + q_t^T\left(q_t^H\right) = \frac{A_t - C_A + (\alpha B + C_B) q_t^H}{(1+\alpha)\, B + C_B}.$$

Total thermal output over the two periods is thus given by

$$Q = \sum_{t=1,2} Q_t = \frac{A_1 + A_2 - 2C_A + (\alpha B + C_B) S}{(1+\alpha)\, B + C_B},$$

which does not depend upon q_1^H. It follows that the total environmental damage is constant *i.e.*, $\frac{dTD}{dq_1^H} = 0$ with $TD \equiv D \sum\limits_{t=1,2} q_t^T$ the sum of environmental damages in the two periods.

A.2 The optimal value of q_1^H

Social welfare is written

$$\begin{aligned}
W\left(q_1^H, q_2^H\right) &= \sum_t \left[\left(A_t - \frac{1}{2} B Q_t^C\right) Q_t^C - (C_A + D)\, q_t^{T,C} - \frac{C_B}{2} (q_t^{T,C})^2\right] \\
&= \sum_t \left(A_t - \frac{B}{2} \frac{A_t - C_A + (\alpha B + C_B) q_t^H}{(1+\alpha)\, B + C_B}\right) \frac{A_t - C_A + (\alpha B + C_B) q_t^H}{(1+\alpha)\, B + C_B} \\
&\quad - \sum_t (C_A + D) \frac{A_t - C_A - Bq_t^H}{(1+\alpha)\, B + C_B} - \frac{C_B}{2} \sum_t \left(\frac{A_t - C_A - Bq_t^H}{(1+\alpha)\, B + C_B}\right)^2
\end{aligned}$$

Notice that the expression of W here above is quadratic in q_t^H. Because $q_2^H = \left(S - q_1^H\right)$, we have an expression that is quadratic in q_1^H, which yields a unique maximum (the coefficient of $\left(q_1^H\right)^2$ being negative). Changes in welfare are monotonic on each side of this maximum.

Let us calculate

$$\frac{\partial W}{\partial q_1^H} = \frac{(\alpha B + C_B)^2 + BC_B}{\left[(1+\alpha)\, B + C_B\right]^2} \left(A_1 - A_2 + BS - 2Bq_1^H\right),$$

which is zero for

$$q_1^{H,*} = \frac{S}{2} + \frac{A_1 - A_2}{2B}.$$

This is the value of q_1^H that yields the largest level of welfare when thermal firms maximize profits. We have

$$\begin{aligned} q_1^{H,*} &> 0 \quad \Leftrightarrow \quad \frac{-(A_1 - A_2)}{B} < S \\ q_1^{H,*} &< S \quad \Leftrightarrow \quad \frac{A_1 - A_2}{B} < S. \end{aligned}$$

A.3 The value of q_1^H under open-loop competition

Using (8) we deduce that the open-loop value of q_1^H is given by

$$q_1^{H,ol} = \frac{S}{2} + \frac{A_1 - A_2}{2B} \frac{(\alpha B + C_B)}{2(\alpha B + C_B) + B}.$$

We have

$$\begin{aligned} q_1^{H,ol} &> 0 \quad \Leftrightarrow \quad \frac{-(A_1 - A_2)}{2B} < \frac{S}{2}\left[\frac{2(\alpha B + C_B) + B}{\alpha B + C_B}\right] \\ q_1^{H,ol} &< S \quad \Leftrightarrow \quad \frac{A_1 - A_2}{2B} < \frac{S}{2}\left[\frac{2(\alpha B + C_B) + B}{\alpha B + C_B}\right]. \end{aligned}$$

Because $\frac{(\alpha B + C_B)}{2(\alpha B + C_B) + B} < 1$, it is straightforward to see that

$$\begin{aligned} q_1^{H,ol} &< q_1^{H,*} \quad \Leftrightarrow \quad \frac{A_1 - A_2}{2B} > 0 \\ q_1^{H,*} &< q_1^{H,ol} \quad \Leftrightarrow \quad \frac{A_1 - A_2}{2B} < 0. \end{aligned}$$

A.4 The value of q_1^H under closed-loop competition

Noticing that

$$\frac{dq_2^T}{dq_2^H} = \frac{-B}{(1 + \alpha) B + C_B},$$

the closed-loop value of q_1^H is given by

$$q_1^{H,cl} = \left(S + \frac{A_1 - A_2}{2B}\right) \frac{2(\alpha B + C_B)}{4(\alpha B + C_B) + B}.$$

We have

$$\begin{aligned} q_1^{H,cl} &> 0 \quad \Leftrightarrow \quad \frac{-(A_1 - A_2)}{2B} < S \\ q_1^{H,cl} &< S \quad \Leftrightarrow \quad \frac{A_1 - A_2}{2B} < \frac{S}{2}\left[\frac{2(\alpha B + C_B) + B}{\alpha B + C_B}\right]. \end{aligned}$$

A.5 Ranking quantities and welfare levels

We hereafter provide the overall ranking of quantities. Once hydro quantities are ranked in period 1, the ranking of welfare levels can be drawn.

A.5.1 First-period peak: $\frac{A_1-A_2}{2B} > 0$

We have $q_1^{H,ol} < q_1^{H,*}$. Let us check whether it is $q_1^{H,ol} < q_1^{H,cl}$. This occurs if and only if

$$\frac{A_1 - A_2}{2B} < \frac{S}{2}\left[\frac{2(\alpha B + C_B) + B}{\alpha B + C_B}\right].$$

Recall that this is the necessary and sufficient condition for both $q_1^{H,cl}$ and $q_1^{H,ol}$ to be smaller than S. Therefore, this condition is to be satisfied and, hence, the converse case is to be ruled out. Also recall that $q_1^{H,*} < S$ if and only if $\frac{A_1-A_2}{2B} < \frac{S}{2}$. Because $\frac{S}{2} < \frac{S}{2}\left[\frac{2(\alpha B+C_B)+B}{\alpha B+C_B}\right]$, the relevant situation is that in which $\frac{A_1-A_2}{2B} \in \left(0, \frac{S}{2}\right)$. Then, we have

$$q_1^{H,cl} < q_1^{H,ol} < q_1^{H,*} \text{ and } W(q_1^{H,cl}) < W(q_1^{H,ol}) < W(q_1^{H,*}).$$

A.5.2 Second-period peak: $\frac{A_1-A_2}{2B} < 0$

We have $q_1^{H,*} < q_1^{H,ol}$. Let us check whether it is $q_1^{H,ol} < q_1^{H,cl}$. This occurs if and only if

$$\frac{-(A_1 - A_2)}{2B} < -\frac{S}{2}\left[\frac{2(\alpha B + C_B) + B}{\alpha B + C_B}\right],$$

which is never the case because the left-hand side is positive. Hence, we have $q_1^{H,cl} < q_1^{H,ol}$. Let us next check whether $q_1^{H,*} < q_1^{H,cl}$. This occurs if and only if

$$\frac{A_1 - A_2}{2B} < \frac{S}{2}\left[\frac{-B}{2(\alpha B + C_B) + B}\right].$$

We can thus distinguish the following two situations:

1. $\frac{A_1-A_2}{2B} \in \left(\frac{-BS}{2[2(\alpha B+C_B)+B]}, 0\right)$, in which case we have

$$q_1^{H,cl} < q_1^{H,*} < q_1^{H,ol} \text{ and } W(q_1^{H,*}) > \max\left\{W(q_1^{H,cl}), W(q_1^{H,ol})\right\}.$$

2. $\frac{A_1-A_2}{2B} \in \left(-\frac{S}{2}, \frac{-BS}{2[2(\alpha B+C_B)+B]}\right)$, in which case we have

$$q_1^{H,*} < q_1^{H,cl} < q_1^{H,ol} \text{ and } W(q_1^{H,ol}) < W(q_1^{H,cl}) < W(q_1^{H,*}).$$

To see how welfare levels are exactly ranked in the first regime of case 2, one should plug $q_1^{H,cl}$ and $q_1^{H,ol}$ into W and compare. Without developing the whole calculation, one can notice that it is $W(q_1^{H,ol}) \leq W(q_1^{H,cl})$ if and only if

$$\frac{A_1 - A_2 + BS}{B}(q_1^{H,ol} - q_1^{H,cl}) \leq (q_1^{H,ol})^2 - (q_1^{H,cl})^2.$$

This is rewritten as

$$\frac{A_1 - A_2 + BS}{B}(q_1^{H,ol} - q_1^{H,cl}) \leq (q_1^{H,ol} - q_1^{H,cl})(q_1^{H,ol} + q_1^{H,cl}).$$

Because $q_1^{H,ol} - q_1^{H,cl} > 0$, we can further write

$$\frac{A_1 - A_2 + BS}{B} \leq q_1^{H,ol} + q_1^{H,cl}$$

or, equivalently,

$$q_1^{H,*} \leq \frac{q_1^{H,ol} + q_1^{H,cl}}{2}.$$

This shows that we have $W(q_1^{H,ol}) \leq W(q_1^{H,cl})$ if and only if the socially optimal hydro quantity does not exceed the arithmetic mean of the open-loop and the closed-loop hydro quantities. The value of $\frac{A_1-A_2}{2B}$ at which $W(q_1^{H,ol}) = W(q_1^{H,cl})$ is such that $(q_1^{H,*} - q_1^{H,ol}) = (q_1^{H,ol} - q_1^{H,*})$, that is

$$\frac{A_1 - A_2}{2B} = -\frac{S}{2}\frac{B\left[2(\alpha B + C_B) + B\right]}{8(\alpha B + C_B)^2 + 9B(\alpha B + C_B) + 2B^2}.$$

Let us now calculate

$$\begin{aligned} & \frac{\partial}{\partial \alpha}\left\{-\frac{S}{2}\frac{B\left[2(\alpha B + C_B) + B\right]}{8(\alpha B + C_B)^2 + 9B(\alpha B + C_B) + 2B^2}\right\} \\ = \quad & \frac{SB}{2}\frac{16B(\alpha B + C_B)^2 + 16B^2(\alpha B + C_B) + 5B^3}{\left[8(\alpha B + C_B)^2 + 9B(\alpha B + C_B) + 2B^2\right]}. \end{aligned}$$

Because this derivative is positive, the value of $\frac{A_1-A_2}{2B}$ at which $W(q_1^{H,ol}) = W(q_1^{H,cl})$ increases with α.

B The impact of long-term contracting on environmental damage

Differentiating (7) with respect to q_t^H yields

$$\left(1 + \frac{dq_t^T}{dq_t^H}\right)p_t' + \alpha\left[\frac{dq_t^T}{dq_t^H}p_t' + \left(1 + \frac{dq_t^T}{dq_t^H}\right)q_t^T p_t''\right] = \frac{dq_t^T}{dq_t^H}C_t'',\ t = 1, 2,$$

so that

$$\frac{dq_t^T}{dq_t^H} = \frac{p_t' + \alpha q_t^T p_t''}{C_t'' - (1+\alpha)\,p_t' - \alpha q_t^T p_t''},\ t = 1, 2. \tag{13}$$

Let $\rho_t \equiv p_t''/(-p_t'Q_t)$ denote the degree of relative prudence in period $t=1,2$. Replacing into (13) and using also the definition of demand elasticity yields

$$\frac{dq_t^T}{dq_t^H} = \frac{-\left(\frac{1}{\varepsilon_t Q_t} - \alpha q_t^T \frac{\rho_t}{\varepsilon_t}\right)}{\frac{C_t''}{p_t} + (1+\alpha)\frac{1}{\varepsilon_t Q_t} - \alpha q_t^T \frac{\rho_t}{\varepsilon_t}},\ t=1,2.$$

We thus have

$$\frac{dq_1^T}{dq_1^H} = \frac{-\left(\frac{1}{\varepsilon_1 Q_1} - \alpha q_1^T \frac{\rho_1}{\varepsilon_1}\right)}{\frac{C_1''}{p_1} + (1+\alpha)\frac{1}{\varepsilon_1 Q_1} - \alpha q_1^T \frac{\rho_1}{\varepsilon_1}} \quad \text{and} \quad \frac{dq_2^T}{dq_1^H} = \frac{\frac{1}{\varepsilon_2 Q_2} - \alpha q_2^T \frac{\rho_2}{\varepsilon_2}}{\frac{C_2''}{p_2} + (1+\alpha)\frac{1}{\varepsilon_2 Q_2} - \alpha q_2^T \frac{\rho_2}{\varepsilon_2}}.$$

A variation in q_1^H triggers the following change in total damage $TD \equiv \sum_{t=1,2} D\left(e\left(q_t^T\right)\right)$:

$$\frac{dTD}{dq_1^H} = D_1'e_1'\frac{dq_1^T}{dq_1^H} + D_2'e_2'\frac{dq_2^T}{dq_1^H}.$$

Substituting from above, we thus obtain

$$\frac{dTD}{dq_1^H} = \frac{D_2'e_2'\left(\frac{1}{\varepsilon_2 Q_2} - \alpha q_2^T \frac{\rho_2}{\varepsilon_2}\right)}{\frac{C_2''}{p_2} + (1+\alpha)\frac{1}{\varepsilon_2 Q_2} - \alpha q_2^T \frac{\rho_2}{\varepsilon_2}} - \frac{D_1'e_1'\left(\frac{1}{\varepsilon_1 Q_1} - \alpha q_1^T \frac{\rho_1}{\varepsilon_1}\right)}{\frac{C_1''}{p_1} + (1+\alpha)\frac{1}{\varepsilon_1 Q_1} - \alpha q_1^T \frac{\rho_1}{\varepsilon_1}}.$$

We have $\frac{dTD}{dq_1^H} < 0$ if and only if

$$\frac{D_2'e_2'\left(\frac{1}{\varepsilon_2 Q_2} - \alpha q_2^T \frac{\rho_2}{\varepsilon_2}\right)}{\frac{C_2''}{p_2} + (1+\alpha)\frac{1}{\varepsilon_2 Q_2} - \alpha q_2^T \frac{\rho_2}{\varepsilon_2}} < \frac{D_1'e_1'\left(\frac{1}{\varepsilon_1 Q_1} - \alpha q_1^T \frac{\rho_1}{\varepsilon_1}\right)}{\frac{C_1''}{p_1} + (1+\alpha)\frac{1}{\varepsilon_1 Q_1} - \alpha q_1^T \frac{\rho_1}{\varepsilon_1}}.$$

With $\eta_t \equiv \left(p_t/q_t^T\right)\left(dq_t^T/dp_t\right) = p_t/C_t''q_t^T$, $t=1,2$, this is rewritten

$$\frac{D_2'e_2'\left[s_2^T - \alpha\rho_2\left(q_2^T\right)^2\right]}{\frac{\varepsilon_2}{\eta_2} + (1+\alpha)s_2^T - \alpha\rho_2\left(q_2^T\right)^2} < \frac{D_1'e_1'\left[s_1^T - \alpha\rho_1\left(q_1^T\right)^2\right]}{\frac{\varepsilon_1}{\eta_1} + (1+\alpha)s_1^T - \alpha\rho_1\left(q_1^T\right)^2}$$

If the marginal damage does not change from one period to the other (that is, $D_1'e_1' = D_2'e_2'$), then the inequality above reduces to

$$\frac{s_1^T - \alpha\rho_1\left(q_1^T\right)^2}{s_2^T - \alpha\rho_2\left(q_2^T\right)^2} > \frac{\frac{\varepsilon_1}{\eta_1} + \alpha s_1^T}{\frac{\varepsilon_2}{\eta_2} + \alpha s_2^T}.$$

B.1 The thermal sector as a competitive fringe

When firm H competes with a competitive fringe, it is $\alpha = 0$. We then have

$$\frac{dq_t^T}{dq_t^H} = \frac{-\frac{1}{\varepsilon_t Q_t}}{\frac{1}{\eta_t q_t^T} + \frac{1}{\varepsilon_t Q_t}} = \frac{-\eta_t s_t^T}{\varepsilon_t + \eta_t s_t^T} < 0, \ t = 1, 2,$$

and so

$$\frac{dD_t}{dq_t^H} = \frac{-D_t' e_t' \eta_t s_t^T}{\varepsilon_t + \eta_t s_t^T} < 0, \ t = 1, 2.$$

This says that a raise in hydropower in period t induces, in that same period, a reduction in thermal output and, hence, a reduction in environmental damage. Because

$$\frac{dq_1^T}{dq_1^H} = \frac{-\eta_1 s_1^T}{\varepsilon_1 + \eta_1 s_1^T} < 0 \quad \text{and} \quad \frac{dq_2^T}{dq_1^H} = \frac{\eta_2 s_2^T}{\varepsilon_2 + \eta_2 s_2^T} > 0,$$

a raise in hydropower in period 1 also induces a raise in thermal output (and so in environmental damage) in period 2. Overall, we have

$$\frac{dTD}{dq_1^H} = \frac{D_2' e_2'}{1 + \frac{\varepsilon_2}{\eta_2 s_2^T}} - \frac{D_1' e_1'}{1 + \frac{\varepsilon_1}{\eta_1 s_1^T}}.$$

This is negative if and only if (11) in the text holds.