



European
University
Institute

Robert Schuman Centre for Advanced Studies

EUI Working Papers

RSCAS 2008/27

FLORENCE SCHOOL OF REGULATION

**Water Misallocation and Environmental Externalities
in Electricity Generation**

Etienne Billette de Villemeur and Annalisa Vinella

EUROPEAN UNIVERSITY INSTITUTE, FLORENCE
ROBERT SCHUMAN CENTRE FOR ADVANCED STUDIES
FLORENCE SCHOOL OF REGULATION

Water Misallocation and Environmental Externalities in Electricity Generation

ETIENNE BILLETTE DE VILLEMEUR AND ANNALISA VINELLA

This text may be downloaded only for personal research purposes. Additional reproduction for other purposes, whether in hard copies or electronically, requires the consent of the author(s), editor(s).

Requests should be addressed directly to the author(s).

If cited or quoted, reference should be made to the full name of the author(s), editor(s), the title, the working paper, or other series, the year and the publisher.

The author(s)/editor(s) should inform the Robert Schuman Centre for Advanced Studies at the EUI if the paper will be published elsewhere and also take responsibility for any consequential obligation(s).

ISSN 1028-3625

© 2008 Etienne Billette de Villemeur and Annalisa Vinella

Printed in Italy
European University Institute
Badia Fiesolana
I – 50014 San Domenico di Fiesole (FI)
Italy
www.eui.eu/RSCAS/Publications/
<http://cadmus.eui.eu>

Robert Schuman Centre for Advanced Studies

The Robert Schuman Centre for Advanced Studies (RSCAS), directed by Stefano Bartolini since September 2006, is home to a large post-doctoral programme. Created in 1992, it aims to develop inter-disciplinary and comparative research and to promote work on the major issues facing the process of integration and European society.

The Centre hosts major research programmes and projects, and a range of working groups and ad hoc initiatives. The research agenda is organised around a set of core themes and is continuously evolving, reflecting the changing agenda of European integration and the expanding membership of the European Union.

Details of this and the other research of the Centre can be found on:

<http://www.eui.eu/RSCAS/Research/>

Research publications take the form of Working Papers, Policy Papers, Distinguished Lectures and books. Most of these are also available on the RSCAS website:

<http://www.eui.eu/RSCAS/Publications/>

The EUI and the RSCAS are not responsible for the opinion expressed by the author(s).

Florence School of Regulation

The Florence School of Regulation (FSR) is a partnership between the RSCAS at the EUI and the Council of the European Energy Regulators (CEER), and it works closely with the European Commission. The Florence School of Regulation is sponsored by leading European energy companies.

The objectives of the FSR are to promote informed discussion of key issues; to provide state-of-the-art training for practitioners; and to produce analytical studies in the field of regulation. It is a European forum dedicated to economic regulation. While its primary focus is on energy regulation, particularly in the electricity and gas markets, it is extending its coverage to other areas of regulation.

This series of working papers aims at disseminating the work of scholars and practitioners on current regulatory issues.

For further information

Florence School of Regulation

Robert Schuman Centre for Advanced Studies

European University Institute

Via delle Fontanelle, 19

I-50016 San Domenico di Fiesole (FI)

Fax: +39055 4685755

E-mail: fsr@eui.eu

<http://www.eui.eu/RSCAS/Research/FSR/Index.shtml>

Water Misallocation and Environmental Externalities in Electricity Generation*

Etienne Billette de Villemeur[†]

Annalisa Vinella[‡]

Abstract

We explore the interactions between environmental externalities and intertemporal market power in electricity generation industries where thermal operators imperfectly compete with operators using scarce water stored in dams. Relying upon a two-period model, we show that, in countries where demand peaks at the first (resp.ly, second) period after water renewal, dynamic market power worsens (resp.ly, ameliorates) resource allocation and environmental health. We then address policy issues. We show that, in general, second best is not decentralized by means of standard tools such as price cap. We argue that the hydraulic process requires specific regulation. We put forward a *quantity*-based version of the contracts for price difference increasingly used in power pools, to be adopted jointly with either a flexible form of taxation or an intertemporal price cap.

Keywords: Power generation, Water allocation, Externalities, Price cap, Contracts for water difference

J.E.L. Classification Numbers: L13, L51, L94; D62; H23

*This paper has been mainly developed while the second author was hosted as a Jean Monnet Fellow at the Florence School of Regulation (EUI, RSCAS), whose support is gratefully acknowledged. We are indebted with Pascal Courty and Massimo Motta for a stimulating discussion. Comments from Franco D'Amore, Eugeniusz Toczyłowski, participants at the 34th EARIE Conference (Valencia), the XIX Siep Annual Meeting (Pavia), the 2007 ASSET Meeting (Padua) as well as seminar participants at the EUI, RSCAS (Florence) and I-COM (Rome) are greatly appreciated. We also thank Fabio Bulgarelli, Jan Moen and Pippo Ranci for providing useful information. The usual disclaimers apply.

[†]Toulouse School of Economics, IDEI and GREMAQ (France)

[‡]University of Bari, DSEMM (Italy); Toulouse School of Economics, GREMAQ (France). *Corresponding author.* E-mail: Annalisa.Vinella@univ-tlse1.fr

1 Introduction

In a plurality of countries, electricity is largely generated by two kinds of plants, namely thermal plants that use fuels like gas and coal and hydraulic plants that use water stored in dams. In New Zealand, power is produced by a thermal operator (22% gas and 12% coal) and a firm that manages the two major reservoirs storage systems (55%)¹. In Finland, 19% of power is hydro-generated, 50% is thermally produced². In Italy, hydraulic and thermal power represent about 13% and 77% of electricity production respectively³.

These technologies display specific features that raise a few important issues.

The thermal technology is based on the usage of hydrocarbon stocks. As the latter do not constitute a scarce resource in the short run, the thermal process is a static one. Production decisions are made independently in peak and off-peak periods, which differ in terms of consumer preferences. This opens the door to the possibility that static market power be exerted in each such period, so as to exploit the specific market opportunities. Moreover, hydrocarbons release polluting emissions that are related to the volume of produced output. Thus environmental externalities are associated with thermal activities.

The hydraulic process relies upon water kept in dams. Unlike hydrocarbons, water is available in a scarce stock. The latter is exhausted in power generation and renewed over time according to the hydrological pattern of the concerned region. Resource paucity makes huge economic rents naturally available. Such rents can be appropriated by exerting static market power in each relevant period. This amounts to conveniently scheduling water usage, taking thermal output as given at any moment in time. However, when hydraulic stations compete with thermal stations, rents can be made particularly large. This entails by strategically (and costlessly) transferring water over time, based on the natural commitment of the available reserve. Using a two-period duopoly model, Crampes and Moreaux [9] (CM hereafter) disclose this further aspect. They show that hydraulic generators can enhance market power by exploiting a first-move advantage *vis-à-vis* their thermal competitors. This is what we refer to as intertemporal (or dynamic) market power.

¹The remainder comes from geothermal sources (7,6%), wind (1,5%) and biomass (1,3%). See Scott and Read [17] for details about power generation in New Zealand.

²The rest of Finnish power (31%) is generated by nuclear stations (Grønli and Costa [14]).

³The residual part of electricity is produced by means of wind, photovoltaic and geothermal plants (Terna S.p.A. [18]).

All in all, in frameworks where thermal and hydraulic operators imperfectly compete, they both exert static market power. Instead, intertemporally strategic behaviour is solely associated with hydraulic activities. Furthermore, hydraulic generation yields no emissions, while so does the thermal process. Environmental externalities interplay with dynamic market power through the strategic interactions between electricity producers. So far this interrelation has not been investigated. Thus the economic implications it yields remain to be clarified. Building on CM, we use a two-period duopoly model to explore the joint work of these two "evils", assess the associated effects on the system efficiency and draw policy implications. Our study brings together a few prior energy-related concerns, namely resource scarcity and control, prices and the impact of energy production on environmental quality⁴.

In our model, competition is taken to occur between firms that use different technologies. As aforementioned, this is the case in countries like New Zealand. However, in other countries, competition takes place between firms managing a mix of production processes. This does not invalidate our approach though. Our model may well represent competition between generators whose technological mixes are rather asymmetric. One may think about Italy, for instance. In 2006, the Italian incumbent of the sector (Enel) was operating with MW 14.379 of hydraulic capacity and MW 26.160 of thermal capacity, while its main competitor (Edipower) had only MW 740 of hydraulic capacity but MW 7.737 of thermal capacity⁵. The message ensuing from our study is thus more general than the simplicity of our stylization might suggest.

The circumstance that water is scarce and exhausted in power production is a key ingredient to our setting. Our analysis does not suit frameworks where water abounds and thermal power is poor. In either case, hydro-producers exert market power by scheduling water usage so as to take advantage of the diversity between peak and off-peak market opportunities. However, in our environment, hydro-producers enhance market power by transferring water over time, based on the information they have about the strategic implications of their own actions on thermal activities. By contrast, in situations where hydraulic electricity predominates, hydro-operators can intensify market power by not releasing some of the available resource. Strategic withdrawal allows them to drive prices above the efficiency point in all relevant periods, the attained

⁴The emphasis that is put at the EU level on environmental issues evidently appears from the extremely rich package of documents published by the European Commission on the topics (available at http://ec.europa.eu/energy/energy_policy/documents_en.htm).

⁵A smaller competitor, Gruppo ENI, was operating with MW 5.466 of thermal capacity and no hydraulic process at all. Further details can be found on the AEEG website.

level depending upon the specific market conditions in each such period. This explains why, in general, in countries where water is available in copious stocks and electricity is nearly all hydro-generated, free disposal is legally banned. Also, public authorities make an effort to solicit and diffuse information on reservoir filling⁶. In those scenarios, environmental problems associated with release of thermal emissions are not particularly relevant because thermal business is poor. On the opposite, they do matter in the settings of our interest, also because of their interaction with intertemporal water allocation. In turn, the distortions associated with strategic misallocation are more important the more the water resource falls short.

The fact that we concentrate on thermal externalities does not mean that the hydraulic process has no environmental impact. It does induce soil and site deterioration indeed. However, unlike thermal emissions, the external damage associated with the hydraulic technology is a fixed cost, *i.e.* it does not depend on output volume. Hence, it is not affected by the specific production policies, which are our main focus. This motivates our choice to neglect hydraulic externalities all along our analysis.

The analysis we develop is rather insightful. From a normative perspective, it conveys the lesson that the impact strategic water transfer has on environmental quality depends upon the specific consumption pattern in the concerned region. More precisely, in settings where consumption peaks at the second period after renewal of the resource stock, exercise of dynamic market power improves water allocation over time and helps alleviate environmental problems, as compared to situations where only static market power is exerted. For instance, this is the case in countries like Finland. By contrast, in settings where consumption peaks at the first period of the water cycle, intertemporal market power worsens water allocation across periods and exacerbates environmental concerns. This is the case of Italy. Essential policy implication is that regulatory interventions are especially useful in countries belonging to the second category. With main (though not exclusive) regard to the latter, we then move to tackle policy issues.

We begin by studying first-best implementation. This requires that both energy price and thermal output stay alike in all periods. The water resource should be allocated so as to smooth the thermal power profile, which minimizes social costs. We show that, when first best is financially viable, it can be implemented by means of a

⁶With hydropower close to 99% of total electricity, Norway represents a good example. As from December 2002, the Norwegian Water Resources and Energy Directorate started providing more detailed information about reservoir filling in the country, as compared to the past. In particular, information about aggregate reservoir levels for four different regions replaced information about aggregate reservoir levels for Norway as a whole (Grønli and Costa [14]).

simple price cap⁷. That is, both intertemporal and environmental distortions can be corrected by simply capping prices at the socially efficient level. Remarkably, this cap is robust to the possibility of collusion between firms. Under binding cap, first best does entail even if operators reach a side-agreement to jointly pursue their private interests. Because the collusive scenario is equivalent to a monopoly endowed with a hydro-thermal generation mix, this means that price-cap regulation is equally successful, whether the sector is competitive or it is served by a single operator managing the two processes. On the other hand, as price-cap regulation attains first best under monopoly, the introduction of (imperfect) competition cannot do better in this context.

In most cases, first best is not financially viable though. In second-best environments, prices are different in different periods and costs are not minimized overall. One way to let prices vary over time, while keeping price discipline, is to impose a different cap in each period. We thus explore a setting where two different caps are in place. We show that the performance of the sector depends on how the responsibility for compliance is assigned. When the two firms are considered to be equally responsible, they are encouraged to coordinate. Importantly, if firms collude with prices fixed at second best, they minimize private costs, as they are residual claimant on the net joint benefits. By doing so, they minimize social costs as well. On the other hand, price-cap regulation generally fails to decentralize second best, if responsibility for cap compliance relapses on the thermal operator only. This occurs when some priority scheme is in place, which puts the hydraulic generator in a privileged position.

From the analogy between collusion and integrated monopoly, we extract a general consideration. Under price cap, monopoly is socially preferable to (imperfect) competition because, unlike oligopoly, it triggers social (and private) cost minimization. This outcome highlights the penalty associated with the introduction of competition and the interdiction of cross-subsidies between activities.

The failure of price-cap regulation rests on the impossibility to discipline water intertemporal allocation through price constraints in the presence of a priority scheme. One thus needs to introduce policies that are able to exert specific control on water management. Hinging on this, we put forward the adoption of the so-called *contracts*

⁷Price cap is one of the most popular regulatory schemes. It tends to survive even in power sectors opened up to competition, especially at early stage of liberalization. One can think about California (Borenstein [7]). In England and Wales, OFFER applied a price cap on power pool purchases over the financial years 1994/5 and 1995/6 (Acutt and Elliott [1]). In Norway, the system operator can introduce a price cap (at the level of the realized system price) in specific areas where few operators are active and suspects arise about exercise of market power (Johnsen [16]).

for water difference, which are meant to remove the perverse incentive to water intertemporal misallocation. This objective is achieved by imposing a sufficiently large penalty on hydro-producers when misallocation is observed. Importantly, such contracts are similar in spirit to other market instruments by now widely adopted in power pools. They can be seen as a *quantity*-based version of the contracts for price differences, which are increasingly used to contain market power in wholesale markets⁸. We further argue that, once the temptation to strategic water transfer is removed, the second-best price profile can be implemented by imposing either a flexible form of taxation or an intertemporal price cap on the thermal operator. Which one is chosen depends on how equilibrium prices compare with second-best prices. Too low a price justifies the introduction of a tax, too high a price calls for a cap. At the implementation stage, the regulator needs basically the same information for either instrument.

The remainder of the paper is organized as follows. Section 2 offers an overview of the related literature. Section 3 describes the model and then presents the first and second-best scenarios. In Section 4, open and closed-loop Cournot competition *à la* CM are revisited. Section 5 illustrates the interaction between environmental externality and intertemporal water (mis)allocation. Section 6 to 8 focus on policy issues. Section 9 concludes.

2 Related Literature

Our study primarily relates to papers that focus on competition in electricity generation with hydropower produced by means of scarce water stored in reservoirs. Within this domain of literature, Arellano [2] explores a Cournot duopoly with a competitive fringe and a mixed hydro-thermal generating portfolio. He evidences that hydraulic operators exert static market power by conveniently choosing the intertemporal hydraulic schedule, without the need of strategic water withdrawal. Bushnell [8] achieves analogous conclusion in a Cournot model of hydro-thermal competition.

In the articles above, the focus is on open-loop Cournot games. Comparing with closed-loop games, CM are able to push the analysis one step further. As aforementioned, they show that, when hydraulic producers compete with thermal producers, the former can also exert dynamic market power. Indeed, they can take advantage of the natural commitment provided by the water stock. Yet CM neglect the environmental

⁸This is the case, for instance, in the power pool in England and Wales.

damage created by the thermal activity and the interaction between the two problems. As already pointed, this is the first contribution of our paper.

A common lesson emerges from the works previously recalled. Water allocation across periods is a suitable instrument for strategic behaviour in the electricity sector, where demand variability creates big business opportunities. Hence, the intertemporal aspect should be taken into account for the design of sound regulatory policies. However, policy issues are missing in the papers aforementioned. Tackling such issues is another contribution of our study.

Policy issues are explored by Johnsen [16] in a context of intertemporal hydropower generation and water storage decisions, with possibility of exchange with neighboring regions. He criticizes price-cap regulation under both competition and monopoly. Specifically, he argues that, under competition, price cap should be removed because it raises the probability of shortages. As for monopoly, he points that whether price cap is useful depends on the period(s) in which it is implemented. While Johnsen investigates the polar cases of competition and monopoly with hydro-production only, we concentrate on hydro-thermal oligopolies *à la* Cournot. This allows us to investigate the impact of price cap on the strategic interactions between operators endowed with market power, on one side, and environmental externalities, on the other side.

Policy issues in a dynamic context with strategic interactions are also core in Garcia, Reitzes and Stacchetti [11] (GRS hereafter). The latter focus on a Bertrand-Nash oligopoly in which two hydraulic producers eventually face either a price-taking thermal fringe or a single thermal producer. The analysis spans over an infinite sequence of periods, each coinciding with a water cycle. This time structure is not very different from ours, though it reflects longer-run dynamics. The similarity arises because, both in GRS and in our model, decisions are ultimately made over two relevant periods, namely present and future in GRS and first and second period of the cycle in our model. With all periods equivalent in terms of demand, in GRS the storage puzzle comes from each firm having incomplete information about future water reserves. By contrast, in our study, intertemporal considerations are important because market opportunities vary over time. Instead, no uncertainty arises within the cycle, as we take the water stock to become commonly known as soon as it is formed and quantities to be observable in each period. Also, since scarce water is never stored from one cycle to the other, uncertainty is irrelevant with respect to subsequent cycles, which we omit to model. This difference reflects the circumstance that, while the analysis in GRS

suits situations where hydropower predominates, we refer to settings where water does not abound and the generation mix is more balanced. This also explains why GRS are not concerned with the externalities created by thermal generation, which are relevant, instead, in our study. In the same vein as Johnsen [16], GRS appraise the impact of price cap on producers' behaviour. They find that, when the cap is set sufficiently low, the reliability of the system can be compromised. Shortage can follow from hydropower totally replacing thermal power. If this concern arises when hydropower predominates, it emerges *a fortiori* in settings where water is scarce. This evidences the necessity of accounting for firms' financial viability while designing regulatory obligations. It thus supports our choice of exploring regulatory interventions that suit second-best frameworks. With regard to the latter, we find that a constant price cap is inadequate, given the intertemporal divergence in second-best prices. For this reason, we look at a pair of period-specific price caps. This necessity is not apparent in GRS. As they do not allow for variable market conditions, they stick on a constant cap.

Our study predicts that, in general, a pair of asymmetric caps is not a successful regulatory tool. An appropriate policy mix rather necessitates, due to the need to control both water management and pollution. The possibility that more policies be adopted at once is explored in Acutt and Elliott [1] (AC hereafter). Unlike the various authors recalled above, but similarly to us, they look at situations where market power coexists with environmental externalities. They stylize a pool of firms that all use the same polluting process to generate electricity in a single period. Thus, importantly, their approach is a static one. They consider the joint implementation of price and environmental regulation⁹. Thanks to firms' symmetry in the pool and absence of dynamics, price-cap regulation does not prove especially problematic in their context. Instead, as already pointed, distortions arise in hydro-thermal oligopolies where water usage is strategically scheduled across periods. Moreover, in AC the joint adoption of economic and environmental regulation is taken as given. On the opposite, the policy mix is motivated in our work where, as aforementioned, it emerges as a need from the failure of popular tools such as price cap. We argue that hydraulic operators should be regulated differently from thermal operators, while in AC both economic and environmental discipline equally concern all the firms, which are homogeneous. Specifically, we propose that regulators exert direct quantity control by offering *ad hoc* contracts to hydro-generators, while AC do not consider forms of economic regulation

⁹Baron [4] studies the same policy combination, with regard to monopoly though.

other than price discipline.

3 The Model

Hinging on CM, we adopt a discrete intertemporal model of Cournot competition in power generation.

Electricity is produced by two firms using different technologies. Firm T manages a thermal process, firm H a hydraulic process. They schedule output over a time span of two periods ($t = 1, 2$) at zero intertemporal discount. The possibility that plants be saturated is ruled out. Hence, operators are never capacity constrained.

Thermal output at period t is denoted q_t^T . The associated variable cost is given by $c(q_t^T)$. The function $c(\cdot)$ is identical in the two periods. It is increasing and convex in its argument ($c'_t \equiv \partial c / \partial q_t^T > 0$, $c''_t \equiv \partial^2 c / \partial (q_t^T)^2 \geq 0$). A fixed cost F^T is also incurred. In each period, the thermal process releases polluting emissions $e(q_t^T)$, which are larger the larger the production ($e'_t \equiv \partial e / \partial q_t^T > 0$). Emissions create environmental damage $D(e(q_t^T))$, with $D(\cdot)$ a smooth function increasing in the level of emissions ($D'_t \equiv \partial D(e(q_t^T)) / \partial e > 0$).

In turn, hydropower is generated by means of water kept in reservoirs. The available stock of water, denoted S , is exogenously given and commonly known in the industry. It can be used between the beginning of the first period, when dams replenish, and the end of the second period, when the reserve is over¹⁰. One unit of water allows to generate one unit of power. Thus firm H faces the intertemporal water constraint

$$\sum_{t=1,2} q_t^H \leq S, \quad (1)$$

where q_t^H expresses hydropower at period t . Since the resource is scarce, the constraint holds, in fact, as an equality. That is, the hydraulic producer exhausts the available reserve within the water cycle. Firm H only incurs a fixed cost F^H as generation costs do not depend on water taking.

With electricity a standardized commodity, 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

¹⁰In practice, water reserves are constituted over time rather than at a specific point in time. Nevertheless, for the purpose of our model, what matters is that the stock is available over two periods.

its argument ($u'_t \equiv \partial u_t / \partial Q_t > 0$, $u''_t \equiv \partial^2 u_t / \partial Q_t^2 > 0$). Electricity consumption is unaffected by the environmental externality. In each period, the demand for power is perfectly known, provided the main part of the yearly variability of demand can be predicted with reasonable accuracy.

3.1 First Best

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

$$W(q_t^T, q_t^H)_{t=1,2} = \sum_{t=1,2} u_t(Q_t) - \sum_{t=1,2} c(q_t^T) - F^T - F^H - \sum_{t=1,2} D(e(q_t^T)). \quad (2)$$

Welfare is the difference between consumer utility and social costs. The latter are given by firms' production costs and environmental damage. The first-best profile of output is pinned down by maximizing the social welfare function subject to (1). Assuming that the first-best allocation is an interior solution¹¹, it satisfies the set of conditions

$$p_t = \mu = c'_t + D'_t e'_t, \quad t = 1, 2, \quad (3)$$

where μ is the Lagrange multiplier associated with the resource constraint. Equations (3) say that, at social optimum, electricity should be equally priced over time. In each period, the energy price should equal the marginal virtual cost of water (μ) as well as the marginal social cost of thermal output. As cost, damage and emission functions are identical in the two periods, firm T should generate the same amount of power at $t = 1, 2$. Observe that demand varies from one period to the other. Thus the hydraulic operator is required to compensate for these variations. This allows the thermal producer to completely smooth its output profile.

Figure 1 provides a graphical illustration of the social optimum. The graph shows that the first-best price is constant over time and equal to the marginal virtual cost of water as well as to the social marginal costs in either period ($p^{fb} = \mu^{fb} = c'_1 + D'_1 e'_1 = c'_2 + D'_2 e'_2$). The first-best allocation is represented by point B, which identifies quantity $q_1^{H,fb}$ and $q_2^{H,fb}$, together with point B_1^T and B_2^T , which in turn identify quantity $q_1^{T,fb}$ and $q_2^{T,fb}$.

¹¹Unless differently specified, the focus on interior solutions will be maintained all along the paper.

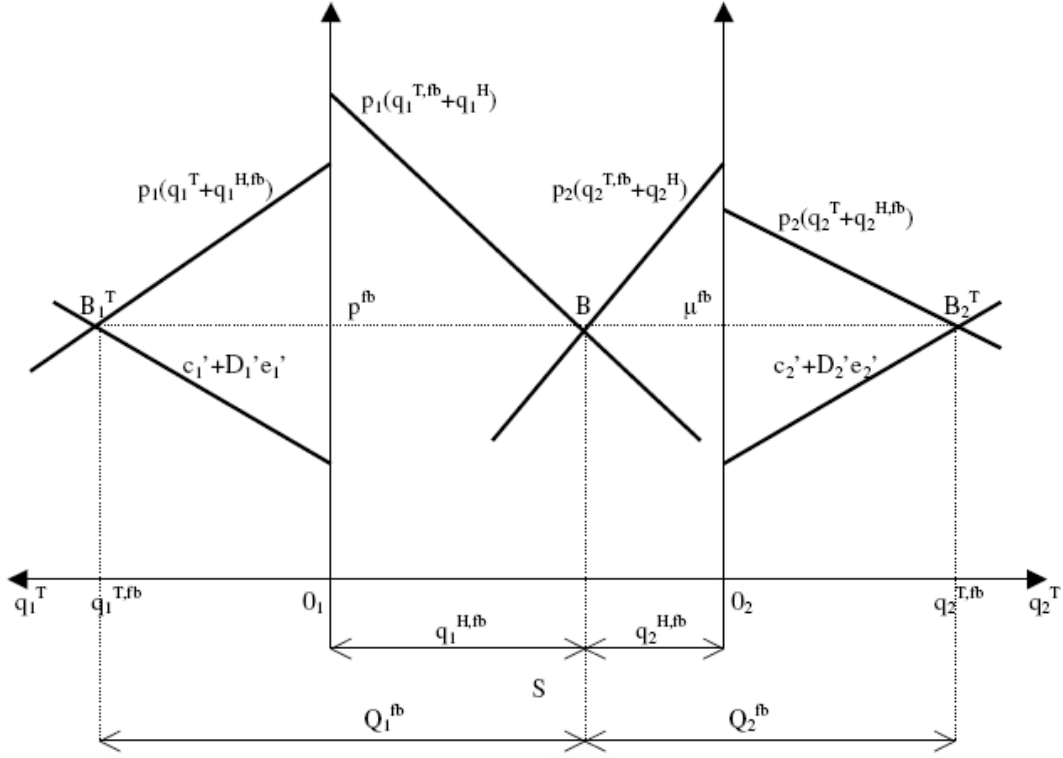


Figure 1: First best.

3.2 Second Best

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

In principle, in our setting, difficulties to break even could arise for either operator. It depends upon the relative size of fixed costs. In practice, generation technologies typically display an inverse relationship between marginal and fixed costs. That is, the thermal process involves high marginal costs together with relatively small fixed costs. By contrast, the hydraulic process associates important fixed costs with (approximately) no variable costs. We know that first-best pricing allows to fully cover thermal variable costs. Thus, if thermal fixed costs are sufficiently small as compared to hydraulic fixed costs, then budget balance might be more concerning for the hydro-producer. For sake of concreteness, we devote attention to this case.

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

the constraint

$$\pi^H(q_t^H, q_t^T)_{t=1,2} = \sum_{t=1,2} q_t^H p_t(Q_t) - F^H \geq 0, \quad (4)$$

which ensures that profits be non-negative for firm H . Letting λ^H the associated Lagrange multiplier, the second-best quantity pair is characterized by the set of conditions

$$\frac{p_t - (c'_t + D'_t e'_t)}{p_t} = \lambda^H \frac{s_t^H}{\varepsilon_t(Q_t)}, \quad t = 1, 2 \quad (5a)$$

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

In the latter, $s_t^H \equiv q_t^H / Q_t$ is the hydraulic market share in period t , $\varepsilon_t(Q_t) \equiv (-p'_t Q_t) / p_t$ the (absolute value of the) price elasticity of market demand in period t and $\tilde{\mu} \equiv \mu / (1 + \lambda^H)$ a deflated measure of the marginal virtual cost of water. Condition (5a) reveals that, at second best, price exceeds thermal *social* marginal costs in either period. Ensuring that firm H breaks even involves that firm T gets a larger-than-first-best per-period markup. Condition (5b) shows that price also exceeds the deflated marginal virtual cost of water in either period. Specifically, 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 , as expressed by the ratio $\lambda^H / (1 + \lambda^H)$. On the other hand, the specific price level in each period depends upon demand elasticity and hydraulic market share. That is, *ceteris paribus*, price is higher in the period when market demand is less elastic. Moreover, it is higher in the period when firm H sells relatively more so as to facilitate break-even.

Combining (5a) and (5b) yields

$$p_1 - p_2 = \frac{\lambda^H}{1 + \lambda^H} (p'_2 q_2^H - p'_1 q_1^H), \quad (6a)$$

where $p'_t \equiv \partial p_t / \partial Q_t$, $t = 1, 2$, together with

$$p_1 - p_2 = \frac{1}{\lambda^H} [(c'_1 + D'_1 e'_1) - (c'_2 + D'_2 e'_2)]. \quad (6b)$$

As (6a) evidences, *ceteris paribus*, the wedge between second-best prices should be larger the more severe the budgetary requirements of firm H . However, as (6b) further suggests, this price divergence comes along with a divergence in marginal social costs. This means that social costs are not minimized. To contain this efficiency loss, the

price difference is kept as small as possible by raising both prices¹². Noticeably, this distortion can be avoided at all when cost, damage and emission functions are linear in quantity. In that case, at second best, price is increased exactly by the same amount in both periods, starting from the first-best level.

A graphical illustration of second best is provided in Figure 2. The graph shows that, at the second-best hydraulic quantities, the marginal revenues from using the hydraulic process, given the amount $q_t^{T, sb}$ of thermal power, are larger in period 1 than in period 2 ($MR_1^H(q_1^{T, sb} + q_1^{H, sb}) > MR_2^H(q_2^{T, sb} + q_2^{H, sb})$). For firm H , the period-1 and period-2 equilibrium are identified by point B_1^H and B_2^H respectively. On the other hand, in each period $t = 1, 2$, price exceeds marginal social costs¹³. For firm T , the period-1 and period-2 equilibrium are represented by point B_1^T and B_2^T respectively.

4 Cournot Competition

We next revisit the analysis of CM and focus on a Cournot duopoly. We begin by presenting the open-loop game, where both firms compete myopically *à la* Cournot in each period. We then consider the closed-loop game, where the hydraulic operator anticipates the effects of current decisions on future performance.

4.1 The Open-Loop Game

When duopolists engage in an open-loop game, firm T takes firm H 's decisions as given and chooses output q_t^T , $t = 1, 2$, so as to maximize the profit function

$$\pi^T(q_t^T, q_t^H)_{t=1,2} = \sum_{t=1,2} q_t^T p_t(Q_t) - \sum_{t=1,2} c(q_t^T) - F^T.$$

The optimal production rule writes

$$p_t + q_t^T p'_t = c'_t, \quad t = 1, 2. \quad (7)$$

¹²An intertemporal divergence arises also at first best when the efficient allocation is not an interior solution. In that case, water should be entirely exhausted 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 the entire stock should be exhausted at period t and thermal production solely occur at period $z \neq t$, as long as the (dual) marginal cost of water is smaller than the social marginal cost of thermal power with $q_t^T = 0$.

¹³As from (5a), in period $t = 1, 2$, price exceeds marginal social costs exactly by the amount $|\lambda^{H, sb} q_t^{H, sb} p'_t(Q_t^{sb})|$.

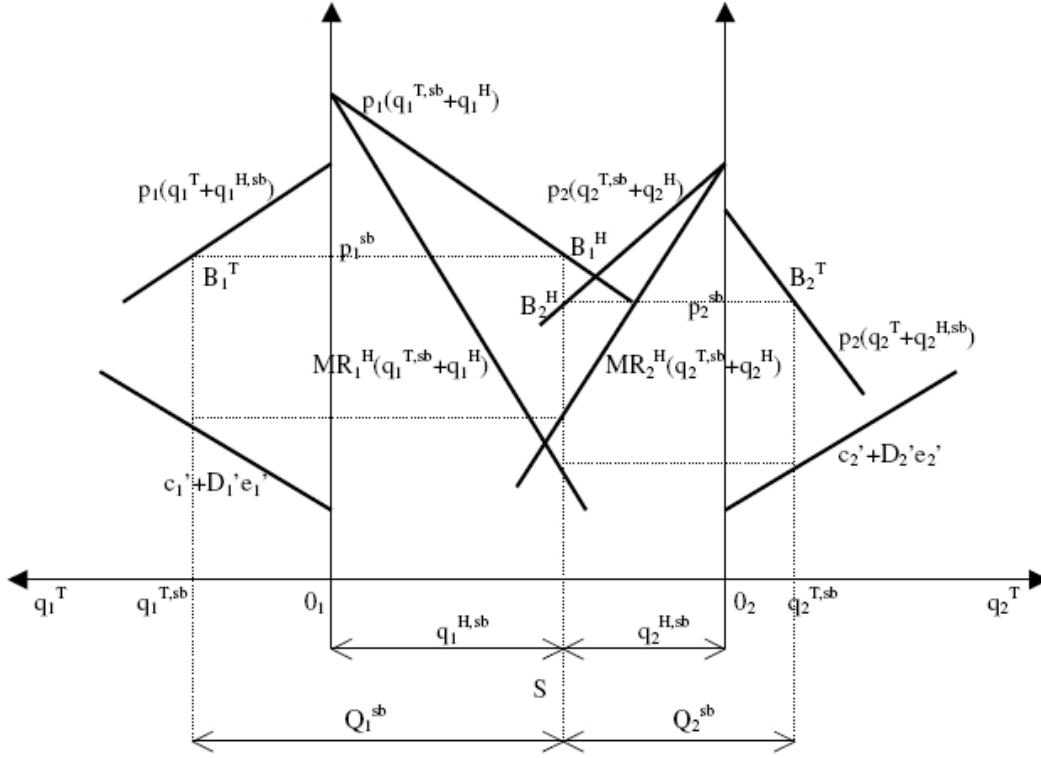


Figure 2: Second best.

Firm T sets quantities so that, in each period, marginal revenues are equal to marginal costs. Condition (7) characterizes the intertemporal profile of thermal output, for any given schedule of hydraulic production. It shows that prices exceed marginal private costs, so that firm T obtains a positive markup in each period. The level of prices also depends on market demand and does not need to stay alike over time. Recall that, by contrast, at first best, prices solely reflect costs, hence they are constant across periods. Yet, they exceed marginal private costs so as to incorporate the externality. This evidences that, in the Cournot setting, market power alleviates environmental problems.

Similarly, firm H takes firm T 's decisions as given and selects 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 hydraulic per-period output, one obtains

$$p_1 + q_1^H p_1' = p_2 + q_2^H p_2' = \mu. \quad (8)$$

Firm H allocates the available water so that marginal revenues are equal across periods and equal to the marginal virtual cost of water. Conditions (8) identify the intertemporal profile of hydraulic power, for any given profile of thermal output. They show that, at Cournot equilibrium, prices exceed the marginal virtual cost of water. This reflects the benefits firm H obtains, at the margin, in the two periods. From CM we know that, under monopoly, a hydro-producer allocates water over time so that the price *exceeds* the first-best level at peak time and is *lower* at off-peak time. This intertemporal distortion follows from the rigidity of water supply¹⁴. Under hydro-thermal duopoly, firm H is a monopolist *vis-à-vis* the demand that is not served by firm T . For a given thermal output profile, water is allocated so as to create enough shortage and raise scarcity rents at peak time.

The equilibrium of the open-loop game is graphically illustrated in Figure 3. The graph shows that, in the Cournot environment, the equilibrium is achieved when the marginal revenues from using the hydraulic process, given the amount $q_t^{T,ol}$ of thermal power, are equal in the two periods and equal to the marginal virtual cost of water ($MR_t^H(q_t^{T,ol} + q_t^H) = \mu^{ol}$, $t = 1, 2$). This equality is represented by point C. On the other hand, in each period $t = 1, 2$, the marginal revenues from using the thermal process, given the quantity $q_t^{H,ol}$ of hydropower equal the thermal marginal costs ($MR_t^T(q_t^{T,ol} + q_t^H) = c'_t$, $t = 1, 2$). The equilibrium is identified by point C_1^H and C_2^H for the hydraulic producer and by point C_1^T and C_2^T for the thermal producer, with higher price in period 1 ($p_1^{ol} > p_2^{ol}$).

4.2 The Closed-Loop Game

Notice that, once the hydraulic production in period 1 is realized, the hydraulic output in period 2 is just what is left out of the available amount of water ($q_2^H = S - q_1^H$). For this reason, firm H is in fact in a position to anticipate how firm T will set quantity in period 2. We now introduce this aspect and focus on a closed-loop game. In this setting, firm H behaves as a perfectly foresighted Stackelberg leader, under the natural commitment of the water reserve. By contrast, the thermal operator still behaves myopically as it faces no intertemporal constraint.

Since the behaviour of firm T is unchanged, it still obeys the profit-maximizing rule

¹⁴If water were abundant and not exhausted in the two periods, then the price would be *higher* than the first-best level in both periods.

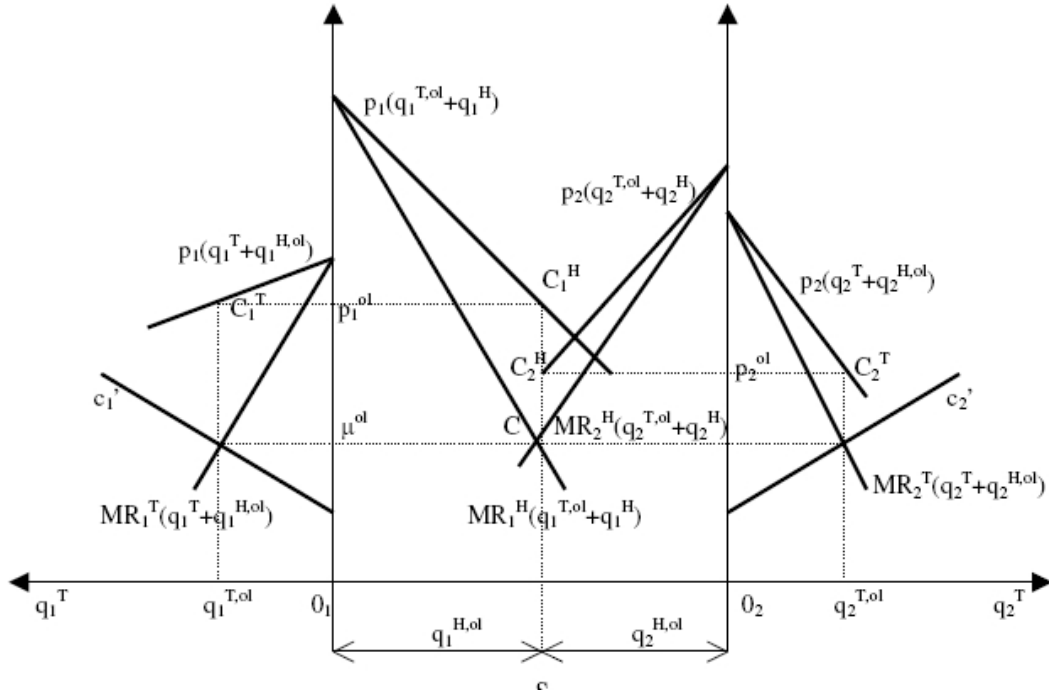


Figure 3: Equilibrium of the open-loop Cournot game.

in (7). As for firm H , profit maximization yields now

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

where $Q_2^{T'} \equiv dQ_2^T/dq_2^H$ and $Q_2' \equiv dQ_2/dq_2^H$. Condition (9), which obtains because $(-dq_2^H/dq_1^H) = 1$, dictates the equality between relevant marginal revenues in period 1 and 2. In the open-loop game, firm H computes period-2 marginal revenues 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 hydro-supply increase at period 2 will be partially compensated by a decrease in thermal supply. Thus, for any given thermal output profile, it now allocates more water to period 2. The hydro-producer playing strategically over time, we shall say that it exerts *intertemporal market power*. At the closed-loop equilibrium, one has

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

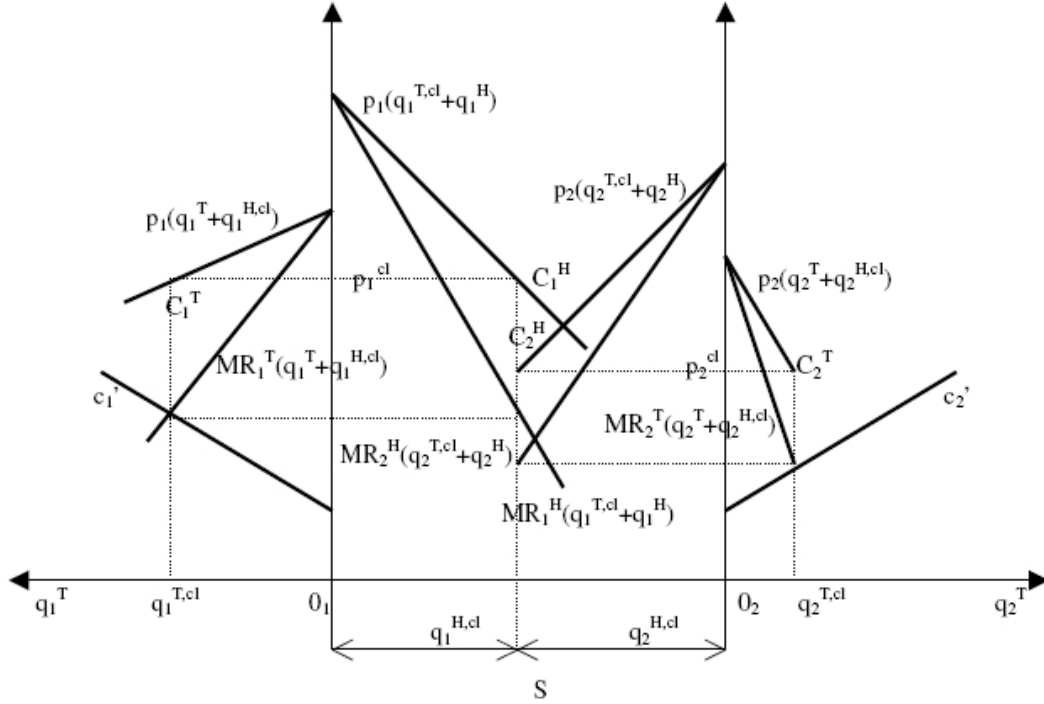


Figure 4: Equilibrium of the closed-loop Cournot game.

This inequality tells that the marginal revenues firm H gets in period 1 exceed those it would get at the second period if an open-loop game were played¹⁵. The equilibrium of the closed-loop game is represented in Figure 4. The graph is to be interpreted as the previous ones, *mutatis mutandis*.

5 Water Misallocation and Externalities

We have seen that strategic water transfer over time raises hydraulic rents. This entails through the realization of a suboptimal intertemporal profile of prices. We hereafter illustrate that this distortion is sometimes counterbalanced by environmental benefits, at least to some extent. Yet, in other cases, it comes along with further inefficiencies.

Two different situations are relevant, according to whether demand peaks at the

¹⁵Clearly, firm H is better off, *ceteris paribus*, at the closed-loop equilibrium. It is more informed about the strategic implications of its own actions. Thus it can more deeply exploit the divergence in per-period market conditions. If it were worse off, then it would abstain from using its knowledge about the competitor's behaviour and revert to the open-loop strategy.

first or second period of the water cycle. Recall that the cycle is structured as follows. The stock is constituted at the beginning of period 1, say spring. Water is used in period 1 and 2, *i.e.* summer and winter. Reservoirs are empty and the cycle is over at the outset of period 2, *i.e.* end of winter. A new cycle starts as the stock is renewed.

Suppose first that demand peaks at the second period of the water cycle. This is the case, for instance, in Finland, where reservoir levels sharply increase during spring and early summer due to snow melting. Outflows are relatively poor in summer and more important in winter, when low temperatures call for intense heating (Grønli and Costa [14]). Things are similar in several other countries, in which reservoirs are located nearby the mountains. In all these countries, under closed-loop competition, water is more efficiently allocated over time, as compared to the open-loop game. Indeed, for any given thermal output profile, hydraulic production can be ranked as $q_1^{H,fb} < q_1^{H,sb} < q_1^{H,cl} < q_1^{H,ol}$ in period 1 and as $q_2^{H,ol} < q_2^{H,cl} < q_2^{H,sb} < q_2^{H,fb}$ in period 2¹⁶. This has important implications. Under closed-loop competition, both the intertemporal profile of prices and that of pollution are less distorted, as compared to the open-loop setting. Therefore, exercise of intertemporal market power is doubly beneficial on efficiency grounds.

Suppose next that demand peaks at the first period of the water cycle. To this consumption pattern has moved Italy in recent years. In Italy, peak-shifting from winter to summer was first registered in 2006, due to overuse of air conditioners and other coolants. In July 2007, electricity consumption broke the historical record for three successive days because of the exceptionally high temperatures¹⁷. Things are reversed in this setting. Under closed-loop competition, water is now less efficiently allocated, as compared to the open-loop game. Indeed, for any given thermal output profile, one has $q_1^{H,cl} < q_1^{H,ol} < q_1^{H,sb} < q_1^{H,fb}$ together with $q_2^{H,fb} < q_2^{H,sb} < q_2^{H,ol} < q_2^{H,cl}$. Hence, bigger distortions appear in the intertemporal profile of both prices and pollution. That is, from a social viewpoint, exercise of intertemporal market power is now doubly detrimental¹⁸.

¹⁶In our notation, *ol* stays for *open loop*, *cl* for *closed loop*, *sb* for *second best* and *fb* for *first best*.

¹⁷Consumption peaked at 56520 MW on July 20, 2007. This value was 70 MW higher than the previous days' peak and 1000 MW higher than the absolute record of 55619 MW, tracing back to June 27, 2006 (compare the Terna Press Release on July 20, 2007; for further details, see Terna S.p.A. [18] as well as the Terna News Archive at the web site www.terna.it).

¹⁸When demand and cost functions are linear in their arguments, total thermal output does not depend on the intertemporal allocation of water. Yet per-period thermal production does vary as water is transferred over time. This reflects firms' incentive to create price divergence between periods. If damage and emission functions are linear as well, then both marginal and total (yearly) damage

We have learnt that whether closed-loop competition is socially preferable to open-loop competition depends upon the consumption pattern in the concerned region. Importantly, this says something on the desirability of policy interventions that prevent intertemporal market power and contain pollution. In countries where demand peaks at the second period of the water cycle, simple *laissez-faire* could be seen as a sound strategy. In the limit, one could even imagine that strategic water transfer be encouraged, especially when the closed-loop allocation is reasonably close to the second-best allocation. By contrast, the need for policy interventions more likely arises in countries where consumption peaks at the first period of the water cycle. In the sequel of our analysis, we take policy interventions to be, indeed, desirable.

6 First-Best Implementation

Suppose that first best is financially viable at the firm level. This is conceivable as long as fixed costs are not too large, provided that efficient prices incorporate both private and external marginal thermal costs. We hereafter show that, under these circumstances, the first-best allocation can be implemented by means of a simple price cap, one of the most popular regulatory schemes in real world.

Take price cap to be fixed at the efficient price level, denoted p^{fb} . Under the cap, power price must be such that

$$p_t \leq p^{fb}, \quad t = 1, 2. \quad (10)$$

One can reasonably conjecture that the constraint will be binding in either period. We shall thus focus on this scenario. The hydro-producer sells power at the same price in both periods. From the firm's viewpoint, it becomes irrelevant in which period water is used. Firm H can thus be expected to make efficient choices, for any given profile of rival production. The intertemporal distortion in resource allocation disappears. Furthermore, with price set at p^{fb} , electricity demand is fixed at the first-best level $Q_t^{fb} = Q_t(p^{fb})$, $t = 1, 2$. Given the amount of hydraulic power $q_t^{H,fb}$, thermal output can only be chosen so as to cover the residual demand. Hence, in each period, firm T

remain constant as water is reallocated. That is, marginal and total externality are the same under open and closed-loop competition and strategic water transfer specifically affects the profile of per-period damage and price. This is relevant in terms of policy strategies, especially if it is considered that, in the linear setting, both first and second-best price stay alike over time.

precisely generates the optimal quantity $q^{T,fb} = (Q_t^{fb} - q_t^{H,fb})$. It follows that efficiency entails in the pollution profile as well. This shows that, when first best is financially viable for either firm, both intertemporal and environmental distortions can be corrected by simply capping prices at the socially efficient level.

Noticeably, the efficient price cap is robust to the possibility that firms collude. Under the cap, the overall payoff of the joint venture constituted by firm H and firm T is given by

$$\begin{aligned}\Pi &= \pi^H + \pi^T \\ &= p^{fb} \sum_{t=1,2} Q_t^{fb} - \sum_{t=1,2} c(q_t^T) - F^H - F^T.\end{aligned}$$

Producers choose quantities so as to maximize Π . This is tantamount to minimizing thermal variable costs $\sum_t c(q_t^T)$. Since cost functions are convex in quantity and identical over time, variable costs are minimized when total thermal output $Q^{T,fb} = (\sum_t Q_t^{fb} - S)$ is evenly shared between periods. As a result, firm H has an incentive to efficiently allocate water because this allows to smooth the output profile of firm T ¹⁹. An important point is that the collusive scenario is substantially equivalent to a monopoly endowed with a hydro-thermal generation mix. This involves that, under price-cap regulation, the socially optimal outcome is achieved, whether the sector is competitive or it is served by a single operator managing the two generation processes.

Further observe that, when fixed costs are small enough and/or environmental damage important enough, under the cap that implements the first-best allocation, firms obtain profits. Importantly, this streams from firm T releasing emissions. It is the necessity to internalize the externality that drives the efficient price strictly above (private) marginal thermal costs. From a social perspective, the circumstance that consumers pay a (first-best) price that leaves net benefits to firms might appear questionable on equity ground. This is especially relevant since net benefits (also) accrue to the polluting firm precisely because it pollutes. It could be argued that the efficient allocation should be made socially equitable. This would call for the adoption of a complementary instrument, such as a tax, that should transfer resources from firm(s) to consumers.

¹⁹In the particular case of a linear cost function, any pair (q_1^T, q_2^T) such that $q_1^T + q_2^T = Q^{T,fb}$ would yield the same total variable costs. The joint venture would be indifferent among all possible quadruples $(q_1^H, q_2^H, q_1^T, q_2^T)$ such that $q_1^H + q_2^H = S$ and $q_1^T + q_2^T = Q^{T,fb}$. In the absence of different incentives, first-best quantities would be produced.

In most cases, first best will not be financially viable at the firm level. Yet, in some situations, it will still be feasible for the industry as a whole. Precisely, this occurs when the following three circumstances materialize at once. Firstly, one of the two operators bears very important fixed costs, which cannot be entirely funded under first-best pricing. Secondly, the other operator has fixed costs that are small enough to still grasp a net benefit under first-best pricing. Thirdly, the net benefit suffices to finance the other firm's deficit, *i.e.* total power production creates enough resources to jointly fund the overall bulk of activities in the sector²⁰. In principle, in our setting, either firm could be the one that obtains profits, depending upon the relative size of fixed costs. Yet, still supposing that the hydraulic producer is less likely to break even under first-best pricing, social optimum with both firms active in the market can be achieved if price cap is complemented by some redistribution policy. Under the latter, the clean activity should be subsidized so as to repay the deficit and thus be preserved in the sector. At this aim, it suffices to levy a tax on firm T . The tax cannot exceed the rent the firm obtains, if financial distress of the latter is to be avoided. The maximum conceivable tax rate is the optimal rate of a Pigouvian tax²¹. Once firms' market power is removed, this rate equals the marginal environmental damage evaluated at the efficient quantity. This is precisely the amount by which the first-best price exceeds private marginal thermal costs. Charging further the firm would mean taking away more than the price margin it gets under first-best pricing. Firm T would go bankrupt.

Observe that the resources extractable from firm T could sometimes exceed those firm H needs to break even. In that case, one could conceive that this residual surplus be transferred to consumers. The role of the tax would then be twofold. Not only it would make full efficiency sustainable in the industry. It would also serve equity concerns by allowing to redistribute from producers to consumers.

In practice, cross-subsidization between producers is seldom permitted. As a result, first best is unlikely implemented, even if it could be sustained at the industry level. In most cases, relevant framework is thus a second-best one.

²⁰This means that the global budget constraint of the industry (rather than that of each firm) is satisfied.

²¹A Pigouvian tax is one that directly applies to released emissions. Thus adoption of a Pigouvian tax requires that emissions be correctly measured. The possibility of doing so (also) varies across pollutants. According to Fullerton [10], public authorities can successfully assess the level of sulfur dioxide emissions by monitoring electric utilities, which are large point sources. When monitoring cannot be performed economically, measurement is still feasible as long as the functional form that links emissions to output is known. In that case, the amount of emissions can be inferred by observing output realizations.

7 Second-Best Implementation

From the previous analysis, we know that, in a second-best framework, prices, thermal output and polluting emissions are not constant across periods, unless cost, damage and emission functions are linear in quantity. One way to let prices differ over time, while keeping price discipline, is to impose a different price cap in each period. Suppose two different caps are in place, each set at the second-best price level of the concerned period, denoted p_t^{sb} . Under the caps, power prices must be such that

$$p_t \leq p_t^{sb}, \quad t = 1, 2. \quad (11)$$

The impact such caps have on the equilibrium of an imperfectly competitive sector depends upon how the responsibility for compliance is assigned to firms. Two possible cases can be considered. The first case arises when a collective responsibility is attributed to all active firms, so that they are all punished when non-compliance with the price constraints is observed. This is a direct form of sector regulation. A second option is that the responsibility is attributed to one firm only, which is thus fined for eventual mismatching. In some sense, a regime of this kind can be viewed as a form of partial regulation. It directly burdens one sole operator, despite price discipline spans over the industry as a whole.

7.1 Collective Responsibility

We begin by exploring the case where all firms are in charge of compliance with the caps. Under collective responsibility, operators need to fix and share output so that the realized market price does not exceed the second-best level in each period. The outcome that materializes depends upon the number and the characteristics of the firms.

Things are simple when the pool is composed by numerous firms that are all basically equivalent, *i.e.* that use either the same generation process or a symmetric mix of processes. The pool can be viewed as a unique representative firm, to which price cap applies. In this environment, operators share responsibility evenly²².

However, in the environment of our interest, only few firms operate. In this scenario, collective responsibility may create incentives to coordinate rather than compete. One

²²Compare Acutt and Elliott [1].

possibility is that operators engage in Nash bargaining. Then the outcome of the negotiation process rests on the bargaining power each firm specifically has. A more extreme scenario is that operators reach a collusive agreement. Suppose this is feasible. Then the programme of the venture formed by firm H and firm T amounts to choosing quantities so as to maximize the joint profits, *i.e.* the net benefits over which they are residual claimant, under resource and price constraints. With the latter binding, total quantities are fixed at their second-best levels and the programme reduces to

$$\underset{q_1^H}{Max} \sum_{t=1,2} p_t^{fb} Q_t^{fb} - c(Q_1^{sb} - q_1^H) - c(Q_2^{sb} - S + q_1^H) - F^H - F^T.$$

The first-order condition of this programme simply dictates that marginal costs be equal over time ($c'_1 = c'_2$). It thus requires that water be allocated so as to smooth the thermal output profile, which allows to minimize private costs. This means that, thanks to collusion, productive efficiency entails at the second-best prices. It further involves that, at the collusive optimum, social costs are minimized in turn.

7.2 Individual Responsibility

We now move to explore the case where only one firm is responsible for the caps. This situation follows from adoption of mechanisms that attach priority to purchase of electricity generated from some specific sources.

In practice, priority schemes are used to favour clean/renewable sources over polluting/exhaustible sources. For instance, in France, under the Law on the orientation of French Energy Policy (2005), EDF has an obligation to purchase electricity produced by wind generators at a preferential tariff. In Italy, since 2005, monetary incentives have been provided to support the development of the photovoltaic process. In Germany, measures in support of renewable energy companies were introduced by the Renewable Energy Supply Act (1990) and the Renewable Energy Feed Law (2000), under which grid operators are committed to buy electricity from renewables at fixed rates. In England and Wales, the Renewables Obligation (2002) compels all licensed electricity suppliers to provide a specified and growing proportion of their power sales from a choice of eligible renewable sources²³.

²³At the European level, rather ambitious objectives appear in the proposal for a new Directive presented by the European Commission in January 2008. According to the proposal, the EU should commit to generate 20% of consumed energy from renewable sources. This goal should be pursued

When a mechanism of this kind applies to a duopolistic sector, the non-prioritized operator basically becomes a regulated monopolist *vis-à-vis* the residual demand. In our model, one such scheme would give priority to the hydraulic operator. The responsibility for compliance with the caps would accrue to the polluting operator. We shall thus focus on this situation. Under the priority scheme, firm H is in a position to decide how to use water over time. Firm T is called upon to complement hydropower with (at least) as much thermal power as it is necessary to satisfy the constraints.

In some cases, second-best pricing does not arise at the equilibrium of both periods, despite caps are fixed at the second-best price levels. To see this, suppose that $p_1^{sb} > p_2^{sb24}$. One possibility is that the cap binds in the first period but does not in the second period. In this case, firm H generates power in both periods allocating water so that the period-1 second-best price equals the "strategic" marginal revenues in period 2

$$p_1^{sb} = p_2 + p_2' q_2^H Q_2'.$$

This scenario is represented in Figure 5. In the graph, point A_1^H and A_2^H identify the equilibrium for firm H and point A_1^T and A_2^T that of firm T in period 1 and 2 respectively. Still with $p_1^{sb} > p_2^{sb}$, another possibility is that the cap slacks in period 1, while it binds in period 2. A situation in which the price constraint is saturated in the off-peak period but not at peak time can solely occur if firm H has an incentive to exhaust water in the first period. This is the case whenever the marginal revenues from hydraulic production at $t = 1$ are larger than the price at $t = 2$ for any $q_1^H \in [0, S]$, so that the equilibrium is characterized by the condition

$$p_1 + p_1' S > p_2.$$

Then, in period 1, the equilibrium price falls below the second-best level whenever the profit maximizing thermal quantity is larger than the quantity that would simply bind the constraint, provided $q_1^H = S$. This situation is graphically represented in Figure 6, where the superscript *pc* indicates the *price-cap* regime and A^H identifies the equilibrium for firm H .

In other scenarios, the cap binds in both periods. Yet, under the considered pri-

by legally compelling member States to match specific national targets. For instance, Italy would be required to make a significant effort to raise energy from renewables up to 17% of consumed energy.

²⁴We find it more useful to focus on this case because, as previously pointed, the need for regulation primarily arises when consumption peaks at the first period of the water cycle.

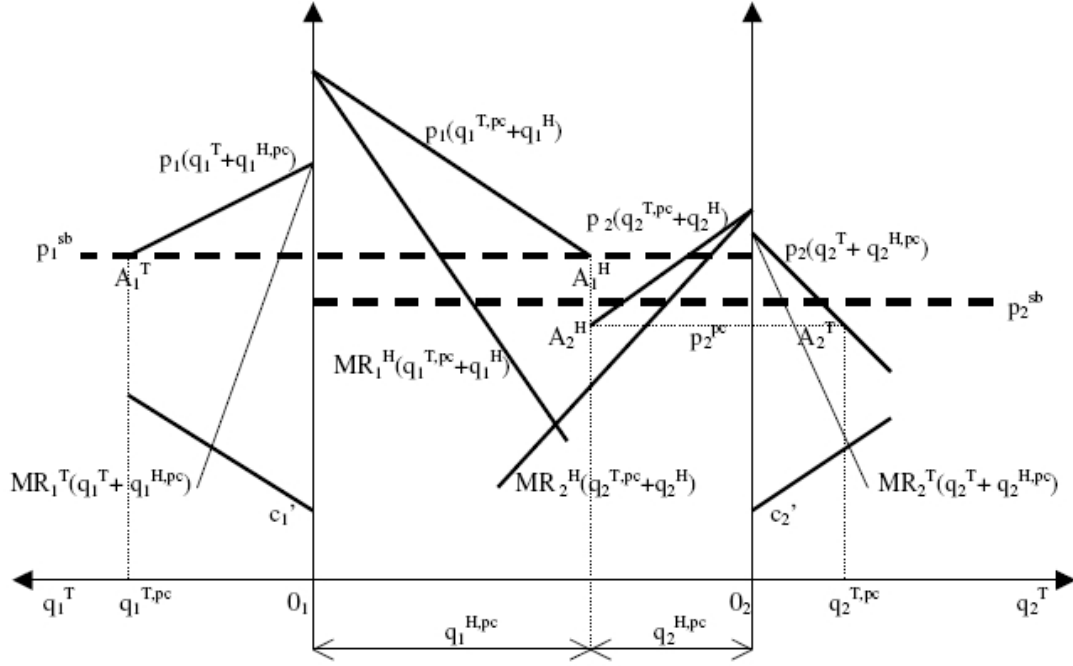


Figure 5: Equilibrium with price cap binding in period 1 only and water shared between periods.

ority scheme, there is no reason to expect the decentralized allocation to be that of second best, albeit equilibrium prices do attain the second-best level. Let us explore those scenarios. When both caps are stringent, the hydraulic operator has an incentive to exhaust water in the high-price period, in which electricity can be sold more conveniently. To check this formally, take again $p_1^{sb} > p_2^{sb}$. With both caps binding, the first-order condition of firm H evaluated at $q_1^H = S$ is written

$$p_2^{sb} - p_1^{sb} < 0.$$

This shows that, if it were feasible, the firm would allocate a negative amount of water to production in period 2. By doing so, it would increase the water to be used in period 1, when electricity can be sold at price $p_1^{sb} > p_2^{sb25}$. Because the firm cannot raise rents by creating scarcity, it "floods" the market when sales are relatively more valuable. Thus, with both caps binding, having water shared between periods is a zero-probability event. The resource being entirely allocated to the high-price period,

²⁵In practice, behaviour of this kind does materialize when hydro-stations pump water during the low-consumption period (when electricity is cheap) so as to refill reservoirs for water usage at peak time.

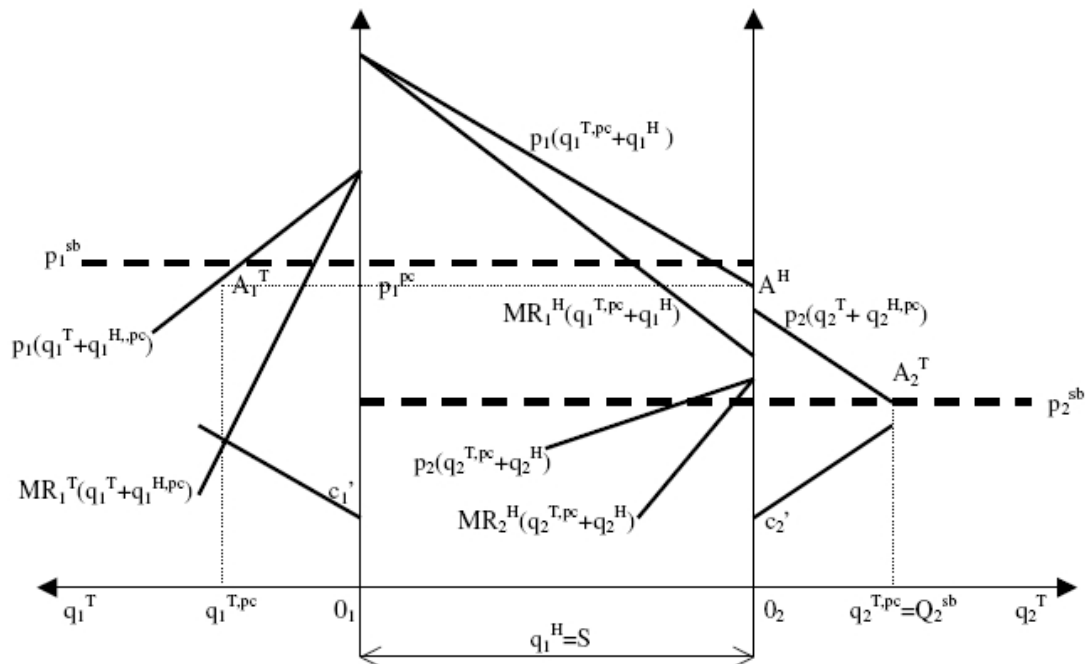


Figure 6: Equilibrium with price cap binding in period 2 only and water entirely used in period 1.

for the price cap to be satisfied in that period, it suffices that firm T complements hydropower. On the other hand, no hydropower is generated in the low-price period. Thus, in the latter, firm T is called upon to produce the second-best industry quantity so as to obey the regulatory obligation. However, as aforementioned, the resulting allocation does not need to coincide with the second-best one. Hence, both the usage of the scarce resource and the release of polluting emissions are likely inefficient. A graphical illustration is provided in Figure 7. As firm H exhausts the stock of water in period 1, the equilibrium is identified by point A^H . Firm T complements hydropower in period 1 by producing $q_1^{T,pc} = (Q_1^{sb} - S)$. It supplies $q_2^{T,pc} = Q_2^{sb}$ so as to satisfy the cap. The equilibrium for firm T is given by point A_1^T and A_2^T in period 1 and 2 respectively.

A few remarks are worth making.

Let us begin with a technical aspect. When price-cap regulation is binding, it does not matter whether firm H anticipates how its competitor will act in the subsequent play of the game. This is so because the hydraulic operator is unable to affect the equilibrium price, despite hydropower sales are given priority. Under this circumstance, closed-loop and open-loop equilibrium end up coinciding. In fact, because in a closed-

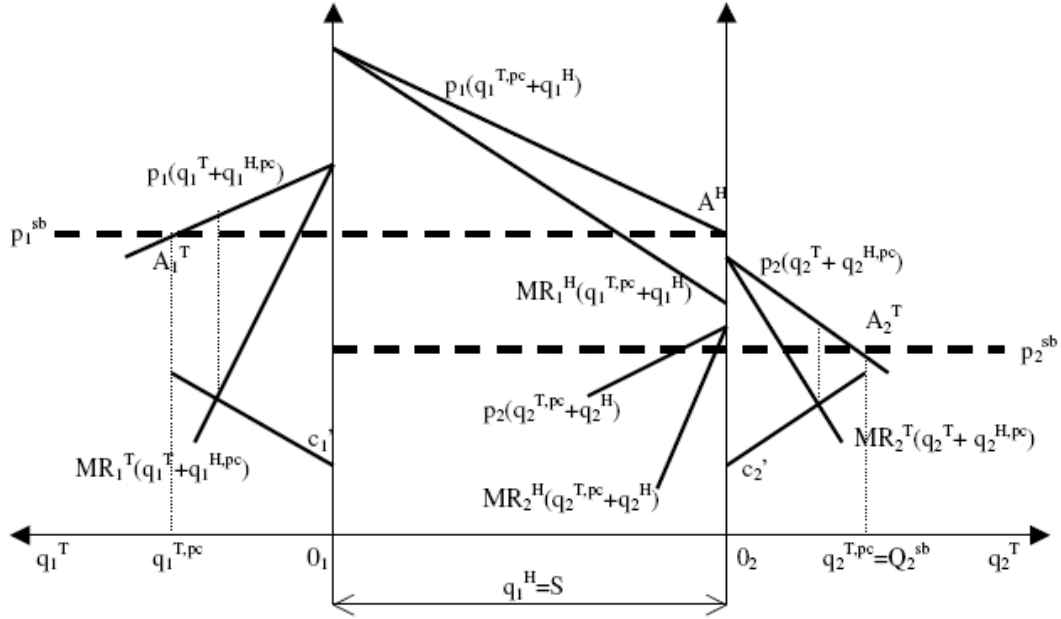


Figure 7: Equilibrium with both caps binding.

loop game the hydraulic producer forecasts the behaviour the thermal producer will take in the second period, for the two equilibria to coincide it suffices that the cap be binding in period 2. This is the situation we refer to in Figure 6 and 7. By contrast, in Figure 5 a scenario is represented, in which the optimal hydropower schedule is determined anticipating how firm T will act in period 2, provided the cap slacks.

We now move to a more general consideration about the desirability of different market structures. The results of our analysis suggest that, as long as regulators resort to traditional price cap, monopoly would be socially preferable to (imperfect) competition in the environments of our interest. With prices fixed at second best, monopoly (which is analogous to collusion) reaches productive efficiency and ensures that social costs be minimized. By contrast, oligopoly only warrants that the equilibrium price will not lie above the second-best level in each period. This unveils a penalty associated with the introduction of competition and the interdiction of forms of cross-subsidization between activities.

8 Water Regulation

Our investigation has revealed that, in the presence of a priority scheme that privileges the hydraulic operator, price-cap regulation generally fails to decentralize second best. The failure rests on the impossibility to discipline water intertemporal allocation through a pair of asymmetric price constraints. This evidences the necessity to exert specific control on water management. In this perspective, we put forward the adoption of the so-called *contracts for water difference* (*CWDs* hereafter), which are meant to remove the perverse incentive to water misallocation. We describe these instruments hereafter.

8.1 Contracts for Water Difference

The regulator identifies the resource quota $\varphi_1^H \in [0, S]$ and $\varphi_2^H = (S - \varphi_1^H)$ firm H should consume in period 1 and 2 respectively. Quota φ_t^H corresponds to the (constrained) efficient amount of hydraulic electricity in period $t = 1, 2$. Recall that the latter is characterized by the "Ramsey condition for oligopoly" in (5b). This involves that fixing the quota is no more demanding for the regulator than fixing a price cap on the sole hydraulic operator would be. Quotas are announced to the firm, which then produces. If the regulator observes that firm H has chosen $q_t^H \neq \varphi_t^H$, $t = 1, 2$, then he obliges the firm to contract over the quantity

$$\begin{aligned} \Delta^H &= |q_1^H - \varphi_1^H| + |q_2^H - \varphi_2^H| \\ &= 2|q_t^H - \varphi_t^H|, \quad t = 1, 2, \end{aligned} \tag{12}$$

at some price ν . The one in expression (12) is a measure of the distance between optimal and realized hydropower profile over the two periods. This is the same as twice the (absolute value of the) difference between optimal and realized hydropower in each period²⁶. The measure Δ^H is positive whenever the regulatory target is mismatched. For instance, observing $q_t^H > \varphi_t^H$ and $q_z^H < \varphi_z^H$, the regulator learns that firm H has inefficiently transferred resource from period z to period t . In that case, *ex post*, the firm is required to purchase a right for excess (resp.ly, insufficient) production in period t (resp.ly, z) at price ν .

²⁶Recall that $q_2^H = (S - q_1^H)$ and $\varphi_2^H = (S - \varphi_1^H)$. This involves that $|q_2^H - \varphi_2^H| = |S - q_1^H - S + \varphi_1^H| = |q_1^H - \varphi_1^H|$. Thus the second equality in (12) follows.

The *CWDs* we put forward are close to the so-called *contracts for price difference* (*CPDs* hereafter). The latter are regulatory instruments frequently adopted in wholesale electricity markets at the aim of reducing generators' market power. Such contracts can be found, for instance, in the power pool in England and Wales. They are put in place between generators and retailers and are structured as follows. If the wholesale price index in any time period proves higher than the regulated strike price, then the generator is obliged to refund to the retailer the difference between strike and actual price for that period. Something similar occurs with our *CWDs*. If the amount of resource used in period $t = 1, 2$ diverges from the target, then the hydraulic generator is compelled to repayment. One can imagine that this payment is made by the producer to the regulator and then transferred to the rest of the collectivity.

The analogy between *CWDs* and *CPDs* is imperfect though. *CPDs* can also work the other way around. That is, if the wholesale price index is lower than the strike price, then the retailer can be called upon to refund the difference between strike and actual price to the generator. In this case, contracts are said to be two-way²⁷. By contrast, *CWDs* are one-way only. The reason is that any excess production in one period is meant to create shortage and raise rents in the other period. Thus the hydraulic generator is punished following to *any* deviation from the regulated quotas.

At the implementation stage, *CPDs* require that the regulator be able to identify the average cost level, at which the strike price is to be fixed. By contrast, *CWDs* can be implemented by simply applying a sufficiently severe (in the limit, an infinite) penalty ν to the distance Δ^H between target and realized hydro-profile. The sole essential requirement is that the overall payment be larger than the net benefits firm H obtains by deviating from the optimal schedule. One way to warrant this outcome is to set $\nu > p_t$. Focusing on this case, one can see more clearly the similarity with the market instruments increasingly adopted in power pools. Basically, under the contract, firm H commits to sell an amount φ_t^H of electricity in period $t = 1, 2$. Sales are made at the market price p_t . The latter is determined depending on competitors' production as well. The operator unfulfilling the contractual obligation would be required to adjust its power profile. At this aim, in each period t , it would need to buy the missing quantity $|q_t^H - \varphi_t^H|$ from other sources at price ν . This would be costly to the firm since the purchased quantity would be resold for cheaper on the market. A mismatch of Δ^H would yield the net penalty $\sum_t (\nu - p_t) |q_t^H - \varphi_t^H|$. Anticipating this loss, the

²⁷The two-way version of the *CPDs* mainly reflects hedging purposes (Green [13]).

hydro-producer prefers to abide by the regulatory target.

8.2 Intertemporal Price Cap/Taxation

Once the regulator has removed the perverse incentive to water misallocation by means of the contracts previously illustrated, he is left with handling the inefficiencies associated with thermal production.

To exert control on the thermal process, and thus to enhance environmental conditions, the regulator needs to resort to a new specific instrument. It is important to select a policy that can be modulated on a per-period basis, so that market conditions can be taken into account in each period. One may think about either a flexible tax or an intertemporal price cap.

Formally speaking, once water quotas are fixed in the *CWD*, the equilibrium price depends upon firm T 's output decisions only. With budget balance a concern for firm H , second-best thermal quantities are those characterized by (5a), while profit-maximizing thermal quantities are those pinned down by (7). Comparing (5a) with (7), it emerges that, *ceteris paribus*, market price is below the second-best level whenever it is $p'_t q_t^T < (D'_t e'_t - \lambda^H p'_t q_t^H)$. In this case, a tax could be levied on firm T so as to induce output contraction and thus raise price. Specifically, the optimal per-period rate of a Pigouvian tax would be

$$\tau_t = D'_t - \frac{p'_t}{e'_t} (\lambda^H q_t^H - q_t^T), \quad t = 1, 2. \quad (13)$$

By contrast, market price is above the second-best level with $p'_t q_t^T > (D'_t e'_t - \lambda^H p'_t q_t^H)$. In this situation, a cap could be imposed so as to decrease price. Suppose an intertemporal price cap of the form

$$\sum_t \alpha_t p_t \leq P,$$

is adopted, with $\alpha_t > 0$, $t = 1, 2$, and P the global threshold. Under this constraint, a unit increase (resp.ly, decrease) in price p_t tightens (resp.ly, relaxes) the constraint by α_t . For second best to be decentralized, the regulator should then set

$$\alpha_t = -\frac{e'_t}{p'_t} \left[D'_t - \frac{p'_t}{e'_t} (\lambda^H q_t^H - q_t^T) \right], \quad t = 1, 2. \quad (14)$$

Comparing (13) with (14), it becomes clear that, at the implementation stage, the regulator needs basically the same information for both the tax and the cap.

9 Conclusions

In this paper, we have explored the interactions between environmental externalities and dynamic market power in oligopolies where electricity is generated by thermal stations that use gas and coal and hydraulic stations that use scarce water stored in reservoirs, which is exhausted and renewed according to a natural cycle.

First of all, our analysis has delivered a normative lesson. With the demand for electricity displaying seasonality, the exercise of dynamic market power can either ameliorate or worsen environmental problems and water usage, depending upon the intertemporal consumption pattern in the concerned region. More precisely, the impact of strategic water transfer is positive in countries where consumption peaks at the second period of the water cycle and negative in countries where consumption peaks at the first period. This has a clear policy implication. Simple *laissez-faire* could represent a sound strategy for the former category of countries. By contrast, appropriate policies should be adopted for efficiency to be restored in the latter class of countries. Yet, implementation raises specific issues, depending upon the efficiency target that is pursued.

We have shown that first best can be decentralized by simply imposing a standard price cap, fixed at the first-best price level. The cap would perform equally well if firms were to collude, rather than compete, or, equivalently, if the sector were rather structured as a monopoly managing both hydraulic and thermal process. This conveys the more general insight that, in first-best settings, regulated (imperfect) competition yields no benefit as compared to regulated monopoly. On the other hand, traditional price cap is a suitable regulatory tool, whatever the degree of competition in the industry.

More often, constrained efficiency is the only feasible target. We have thus moved to a second-best framework. We have shown that price-cap regulation generally fails to decentralize second best, when responsibility for cap compliance entirely relapses on thermal generation. This typically occurs when some priority scheme is put in place to support the hydraulic technology for environmental reasons. Incentive schemes of this kind are adopted in several countries (e.g., France, Italy, Germany) for stimulating

power generation from clean/renewable sources. The alternative option of imposing collective responsibility would encourage firms to collude. Noticeably, collusion, which is analogous to monopoly, would improve market performance by inducing cost minimization. This channels the more general message that, in second-best environments, regulated monopoly is socially preferable to regulated (imperfect) competition. Moreover, traditional price cap becomes less powerful a regulatory tool as the degree of competition (weakly) raises in the industry.

The privileges assigned to power from renewable sources are largely seen as a reasonable pledge for the environmental prize. Our investigation has evidenced that they are not free from shortcomings. In particular, they may interfere with the incentive power of other schemes simultaneously in place. Price-cap regulation fails to decentralize second best because the priority scheme makes the caps unable to discipline water intertemporal allocation. This means that application of priority schemes may create the necessity to further intervene in the sector.

To trigger efficient outcomes, regulators should (also) provide specific incentives to desirable water management. The *contracts for water difference* we have proposed are designed to serve this purpose. We have argued that second best can be achieved by coupling such contracts, which are similar in spirit to the contracts for price difference increasingly used in power pools, with either a flexible form of taxation or an intertemporal price cap. By exploring this mix of policies, we have also shed light on the joint use of regulatory instruments in imperfectly competitive markets, a matter that has been poorly explored so far.

References

- [1] Acutt, M., and C. Elliott (1999), "Regulatory Conflict? Environmental and Economic Regulation of Electricity Generation", *FEEM Working Paper* No. 40.99
- [2] Arellano, M.S. (2004), "Market Power in Mixed Hydro-Thermal Electric Systems", *Centro de Economía Aplicada*, Universidad de Chile, *Working Paper* No.187
- [3] Barnett, A. H. (1980), "The Pigouvian Tax Rule under Monopoly", *American Economic Review*, 70(5), 1037-1041
- [4] Baron, D. P. (1985), "Noncooperative regulation of a nonlocalized externality", *Rand Journal of Economics*, 16(4), 553-568
- [5] Billette de Villemeur, E., and A. Vinella (2007), "Externalities, Regulation and Taxation in Electricity Generation", in IEE and SEP (eds.), *The European Elec-*

- tricity Market: Challenge of the Unification*, Proceedings of the 4th EEM Conference
- [6] Billette de Villemeur, E., and A. Vinella, "Regolamentazione Parziale di Quantità", *Rivista di Politica Economica*, forthcoming, 2007
 - [7] Borenstein, S. (2002), "The Trouble with Electricity Markets: Understanding California's Restructuring Disaster", *Journal of Economic Perspectives*, 16 (1), 191–211
 - [8] Bushnell, J. (2003), "A Mixed Complementarity Model of Hydrothermal Electricity Competition in the Western United States", *Operations Research*, 51(1), 80–93
 - [9] Crampes, C., and M. Moreaux (2001), "Water resource and power generation", *International Journal of Industrial Organization*, 19, 975–997
 - [10] Fullerton, D. (2001), "A Framework to Compare Environmental Policies", *Southern Economic Journal*, 68(2), 224–248
 - [11] Garcia, A., J. D. Reitzes and E. Stacchetti (2001), "Strategic Pricing when Electricity is Storable", *Journal of Regulatory Economics*, 20(3), 223–247
 - [12] Green, R. (2004), "Did English Generators Play Cournot? Capacity With-holding in the Electricity Pool", *CMI Working Paper* No. 41
 - [13] Green, R. (1999), "The Electricity Contract Market in England and Wales", *The Journal of Industrial Economics*, 47(1), 107–124
 - [14] Grønli, H., and P. Costa (2003), "The Norwegian Security of Supply Situation during the Winter 2002/-03. Part I - Analysis", *Working Paper* prepared for the Council of European Energy regulators
 - [15] Grønli, H., and P. Costa (2003), "The Norwegian Security of Supply Situation during the Winter 2002/-03. Part II - Conclusions and Recommendations", *Working Paper* prepared for the Council of European Energy regulators
 - [16] Johnsen, T. A. (2002), "Hydropower generation and storage, transmission constraints and market power", *Utilities Policy*, 10, 63–73
 - [17] Scott, T. J., and E. G. Read (1996), "Modelling hydro reservoir operation in a deregulated electricity market", *International Transactions in Operational Research*, 3(3), 243–254
 - [18] Terna S.p.A., Rete Elettrica Nazionale (2007), *Dati Provvisori di Esercizio del Sistema Elettrico Nazionale 2006*