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# Transportation and Storage under a Dynamic Price Cap Regulation Process

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## Abstract

We study the welfare effects of Price Cap Regulation (PCR) and the strategic behavior it may induce in gas transportation networks by analyzing a stylized gas network within the framework of a multi-period game model under three scenarios: No regulation, a dynamic setting where the price cap adjustment mechanism is not endogenized by the players, and a dynamic setting where it is endogenized by the players.

**Key Words:** Gas market, dynamic game, price cap regulation.

## Résumé

Nous analysons l'impact sur le bien-être d'une règlementation basée sur le plafonnement des prix, en caractérisant le comportement stratégique qu'un tel plafonnement peut induire dans un réseau de distribution de gaz. Nous étudions un réseau stylisé dans un contexte dynamique et saisonnier et comparons trois scénarios : absence de règlementation, règlementation avec ajustement dynamique du plafond dans le temps, et un troisième où les joueurs endogénisent la mécanique d'ajustement du plafond.

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# 1 Introduction

Gas markets liberalization is accompanied in many cases by the requirement to unbundle gas sales from transportation and storage services. In the U.S.A., this separation is mandatory under FERC Order 636. Legal unbundling is forced in Europe through the 2003 Gas Directive. In particular, Art. 19 (1) of the 2003/557EC Gas Directive requires that access to storage and line pack be offered for efficient use of the networks.

The unbundling of services and the requirement to establish Open Access regime in network industries to promote competition is analyzed extensively in the literature. One stream of this literature deals primarily with the optimal access fees issue (see for example Armstrong et al. 1996 and Armstrong and Vickers 1998). Another stream deals with the regulation of network industries as a means to protect consumers from monopolistic behavior. Price cap regulation (PCR) is adopted in many countries and is one of the preferred regulatory mechanisms for network industries (Beesley and Littlechild 1989, Brennan 1989, Isaac 1991). Under a pure PCR, a cap is imposed on the average prices that the regulated company may charge for its services. This price cap is adjusted over time to take into account inflation effects (Armstrong et al. 1994, Bernstein and Sappington 1999).

Different PCR schemes are used in practice. Armstrong et al. (1994) report that fixed weights (tariff basket or Laspeyres index approach in practice) and average revenue regulation (lagged average revenue approach in practice) schemes are widely used to regulate utilities in England and in other counties (Jamasb and Pollitt 2007). The impact of price cap regulation has been studied under various perspectives, namely performance attributes (Domah and Pollitt 2001), investment effects (Buehler et al. 2010), and welfare effects.

With respect to the effect of price cap changes on consumer's surplus, Armstrong and Vickers (1991) show that tightening an average revenue constraint may deteriorate consumer's welfare in a multi-product case. In the single product framework, consumer's welfare is improved. Law (1995) shows that with independent demands, tightening an average revenue constraint can reduce consumer welfare when products marginal costs are different. Cowan (1997) concludes that no regulation can be better than a very tight price cap in average revenue regulation. Concerning the Laspeyres index approach, Cowan (1997) shows that a tight price cap could result in a welfare depreciation with respect to no regulation, whereas, under certain conditions, the Laspeyres index approach based on lagged quantities will always improve welfare. In all the above papers, the authors are assuming independent demand functions. Kang et al. (2000) investigate conditions under which a price cap reduction impacts consumer's welfare negatively. Using linear demand functions for a two product firm and fixed weights factors in the regulatory constraint, they find that if demands are independent, tightening the price cap constraint is always beneficial to consumers, whereas if demands are interdependent then a reduction in the price cap may deteriorate consumer's surplus.

While it is widely accepted that a PCR is an efficient regulatory mechanisms, it is not necessarily immune from firms' strategic behavior. In the case of Chile, it is reported that there are evidences that stock market prices of the regulated firms react differently to cost announcements in review years than in non review years (Di Tella and Dyck 2002). In the case of benchmarking use within incentive-based regulation frameworks, regulated firms can also act strategically by gaming the regulator's benchmarking and not achieving the announced performance improvements (Jamasb et al. 2003).

This paper contributes to the literature on the impact of PCR under the perspective of welfare effects. We specifically consider the case of a stylized gas transportation and storage network with seasonal demand variation. In that case, contrary to most of the literature about welfare effects, demands for transportation and storage services are not independent. Interdependent demand has been studied in Kang et al. (2000); however, our setting differs significantly from theirs, as interdependency of demand here is not exogenous, but rather arises from the network industry structure, and from seasonality and network capacity constraints. Moreover, with seasonal demand variation, when pipeline capacity becomes binding, then storage and quantities become substitutes on an inter-temporal basis. Accordingly, the degree of demand interdependency may change over time, as a result of the regulation. A second contribution of the paper is then the analysis of the impact of PCR in a dynamic setting. To our knowledge, no dynamic model of the impact of PCR on demand functions and welfare effects has been proposed in the literature. Finally, our paper also contributes to the literature on strategic implications of PCR by considering that regulated players may anticipate the changes in the PCR and demands over time and adjust their pricing decisions accordingly.

We show that, as a consequence of a tariff basket PCR, the pipeline company reduces its access to pipeline tariff while increasing the storage access fee. The reduction in pipeline access fees translates into higher transmitted quantities both for final consumption and storage, as long as pipeline capacity is not binding. As a consequence, downstream prices are reduced, which implies an increase in consumer surplus. As long as the pipeline capacity is not binding, we show that tightening the price cap constraint is always beneficial to consumers, even though demands for storage and transportation are not independent. However, the reverse is true when the pipeline capacity is fully used; in that case, storage quantities start decreasing and prices in the high demand season increase, which results in reduced consumer surplus.

Over time, PCR eventually results in binding pipeline capacity and reduced demand for storage. We find that this outcome occurs whether the pipeline firm acts strategically or not. Moreover, we find that when the capacity constraint is binding, the benefits of the mechanism are essentially captured by the downstream distribution companies.

The remainder of the paper is organized as follows. Section 2 describes the model and notation. Section 3 solves the static game between the pipeline and downstream companies for a given year and for given weights and cap. Section 4 illustrates the impact of imposing a price cap over time, assuming both myopic and strategic behavior from the pipeline company. Section 5 is a conclusion.

## 2 The model

We consider a stylized gas network. The upstream market is a competitive market with no production shortage in any period. The downstream market is a competitive market where $n$ identical distribution companies contract for the gas in the upstream market and arrange for transportation and storage services with an independent pipeline company. The latter is operating a pipeline connecting the gas producers to the consumer market. A storage facility is located at the city gate (consumer market). Each distribution company is a price taker in the upstream market. The $n$ companies operate within the framework of the standard Cournot game in the downstream market. They are endowed with equal capacity rights; in the case of a congested pipeline, a prorating mechanism is used to share the available capacity. This stylized system represents the physical gas market (Figure 1).

We consider a dynamic system where the gas year is divided into two periods or seasons. Season 1 is a low-price period while Season 2 is a high-price one. The storage facility is used for seasonal storage and not diurnal or peak-shaving storage. (Peak shaving storage is used for hedging activities on a daily or hourly basis). Seasonal storage facilities are filled during the low-price season and emptied during the high-price season.

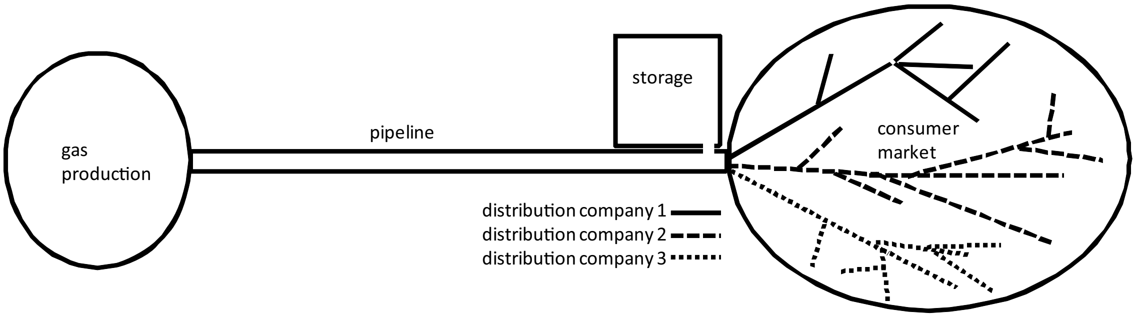

Figure 1: Stylized gas network

In order to simplify notation, both the pipeline capacity (in units of volume per year) and the slope of the annual demand function are normalized to 1, so that the volume unit is denoted $u$ and the currency unit is denoted $\mathcal{S}$.

The integrated pipeline and storage company is subject to a price cap regulation. Thus, the company has some flexibility in fixing the access fees to its pipeline and storage facilities, provided that a weighted average of those prices is less than the price cap imposed by the regulator. The pipeline company is thus subject to

$$w_{1t}g_t + w_{2t}f_t \leq \theta, \tag{1}$$

where:

$\theta$ : price cap,
$g_t$ : price for the access to the pipeline during year $t$ ($\mathcal{S}/u$),
$f_t$ : price for the access to the storage (including withdrawal and injection fees) during year $t$ ($\mathcal{S}/u$),
$w_{1t}, w_{2t}$: weight factors at year $t$ ($u/\mathcal{S}$).

The tariff basket PCR is widely used in the gas industry. In tariff basket PCR, $w_{1t}$ and $w_{2t}$ are defined as follows:

$$w_{1t} = \frac{T_{t-1}}{(g_{t-1}T_{t-1} + f_{t-1}S_{t-1})} \tag{2}$$

$$w_{2t} = \frac{S_{t-1}}{(g_{t-1}T_{t-1} + f_{t-1}S_{t-1})} \tag{3}$$

where:

$T_{t-1}$ : total gas transported during year $t-1$ ($u$),
$S_{t-1}$ : total gas stored during year $t-1$ ($u$).

Consumer demand for gas in the downstream market is assumed to be constant over time, deterministic and linear, with a slope normalized to 1, and given by

$$D_{tm} = L_m - P_m,$$

where $P_m$ is the price ($\mathcal{S}/u$) in season $m$ of the gas year, $D_{tm}$ is the total gas ($u$) delivered to the consumers in season $m$ of year $t$, and $L_m$, the intercept in season $m$ of the gas year ($u$), is such that $1 < L_1 < L_2$.

We assume that the pipeline capacity constraint is binding in the second (high-price) season, justifying the need for storage in the first season. Since distribution companies have equal capacity rights, the quantity (in $u$) distributed by each company in the second season is thus equal to $\frac{1}{n}$. As long as storage capacity is available, if the pipeline is used at full capacity in the second season, then distribution companies have incentives in storing gas in the first season in order to sell it in the second season at higher prices. In the first season, pipeline capacity may or may not be binding, depending on the quantity of gas purchased and stored for the second season, that is, quantities for storage compete with demand in the first season for pipeline capacity.

Denote:

$q_{tmj}$: gas contracted and distributed ($u$) by firm $j$ in season $m$ of year $t; m = 1, 2,\ j = 1, \ldots, n,\ Q_{tm} = \sum_{j=1}^{n} q_{tmj}$,
$s_{tj}$: storage ($u$) of firm $j$ in year $t$, that is, gas contracted by firm $j$ in season 1 and distributed in season 2 of year $t$, $j = 1, \ldots, n$, $S_t = \sum_{j=1}^{n} s_{tj}$,
$T_t$: total gas ($u$) transported by the pipeline company in year $t$, $T_t = Q_{t1} + Q_{t2} + S_t$,
$D_{tm}$: total gas ($u$) delivered to the consumers in season $m$ of year $t$, $D_{t1} = Q_{t1}$, $D_{t2} = Q_{t2} + S_t$,
$c_{tm}$: marginal cost of production ($\mathcal{S}/u$) in the upstream market in season $m$ of year $t$, which is also the marginal cost of contracting for gas by a distribution firm in the upstream market in season $m$ of year $t, m = 1, 2,$

$\Pi_{tj}$: total profit $(\mathcal{S})$ for distribution firm $j$ in year $t$, $j = 1, \ldots, n$
$\Pi_{t0}$: profit $(\mathcal{S})$ of the pipeline company in year $t$
$r_t$: unit transportation cost $(\mathcal{S}/u)$ in year $t$
$a_t$: unit storage cost $(\mathcal{S}/u)$ in year $t$.

Finally, we also use the notationally convenient conventions

$$\begin{aligned} \kappa &\equiv \frac{n+1}{n} \\ A &\equiv L_1 - c_1 \\ B &\equiv L_2 - c_1. \end{aligned}$$

# 3 Static equilibrium

In this section, we state the equilibrium strategy of the downstream distribution firms and the pipeline company in a given year for a given price cap and weights, assuming that the weight adjustment mechanism is not endogenized by the players. The computational details are given in A. To alleviate the notation, we omit the time argument when no ambiguity may arise.

## 3.1 Production and storage in the downstream market

Assuming identical firms, the equilibrium productions and storage are obtained by simultaneously solving for the optimality conditions. We discard as non interesting the case where the equilibrium solution is such that there is no distribution in the downstream market in the first season. This yields the following two possibilities for the equilibrium in the downstream market:

1. **Capacity constraint not binding in the first season**
   The equilibrium $\left(Q^l, S^l\right)$ is given by:

$$\begin{aligned} Q^l &= \frac{A-g}{\kappa} > 0, && (4) \\ S^l &= \left[\frac{B-g-f-\kappa}{\kappa}\right]^+. && (5) \end{aligned}$$

2. **Capacity constraint binding in the first season**
   The equilibrium $\left(Q^b, S^b\right)$ is given by:

$$\begin{aligned} Q^b &= 1 - S^b > 0, && (6) \\ S^b &= \left[\frac{B-A-f}{2\kappa}\right]^+. && (7) \end{aligned}$$

Notice that there is no discontinuity in the downstream equilibrium response when the first season capacity constraint becomes binding or when storage becomes non interesting.

We assume the following conditions on the model parameters. We will see below that these conditions are equivalent to our assumptions about the downstream market (positive distribution during the first season and binding capacity during the second season).

$$\begin{aligned} A - r &> \kappa && (8) \\ B - A + a + 2\left(c_1 - c_2\right) &\geq 2\kappa && (9) \\ 2B - A - r + 2\left(c_1 - c_2\right) &\geq 3\kappa && (10) \\ B - A - a &< 2\kappa. && (11) \end{aligned}$$

## 3.2 Transportation and storage access fees

### 3.2.1 Access fees before regulation

The pipeline company maximizes its profits from its two activities. The optimization problem is thus:

$$\max_{g,f} \Pi_0 = (g-r)(T(g,f)) + (f-a)S(g,f)$$

where $T(g,f)$ and $S(g,f)$ are the total quantities transported and stored, obtained from the solutions in the downstream market. Notice that we do not rule out the possibility of negative access prices (subsidies), provided the total profit is positive. We assume that the parameters are such that, in all cases, marketed quantities are positive in the first season and capacity is binding in the second season. Thus, we get the following solutions, corresponding to four possible downstream equilibria (see B for details).

1. **Capacity constraint not binding in the first season with storage**
   Optimal prices for the pipeline company are given by:

$$\begin{aligned} g^l &= \frac{1}{2}(A+r+\kappa), \\ f^l &= \frac{1}{2}(B-A+a-2\kappa). \end{aligned}$$

   The corresponding downstream equilibrium is then

$$\begin{aligned} Q_1^l &= \frac{1}{2\kappa}(A-r-\kappa) \\ S^l &= \frac{1}{2\kappa}(B-r-a-\kappa). \end{aligned}$$

   This solution implies that margin from the pipeline operation is positive, but margin from the storage operation is negative, and it could even be advantageous for the pipeline company to subsidize storage in order to increase demand, with $f^l < 0$.

2. **Capacity constraint not binding in the first season without storage**
   The optimal price and quantities are:

$$\begin{aligned} g^{l0} &= \frac{1}{2}(A+r+\kappa) \\ Q_1^{l0} &= \frac{1}{2\kappa}(A-r-\kappa), \end{aligned}$$

   provided the price for storage is sufficiently high.

3. **Capacity constraint binding in the first season with storage**
   The optimal prices for the pipeline are

$$\begin{aligned} f^b &= f^l = \frac{1}{2}(B-A+a)-\kappa \\ g^b &= \frac{1}{4}(B+3A-a-2\kappa). \end{aligned}$$

   The corresponding downstream equilibrium is then

$$\begin{aligned} Q_1^b &= \left(\frac{1}{2}+\frac{a+A-B}{4\kappa}\right) \\ S^b &= \left(\frac{1}{2}-\frac{a+A-B}{4\kappa}\right). \end{aligned}$$

   It can be shown again that margin is positive for the pipeline operation, while it could happen that a subsidy to storage operation be profitable for the pipeline company.

4. **Capacity constraint binding in the first season, no storage**

The optimal solution is given by:

$$\begin{aligned} f^{b0} &\geq B - A \\ g^{b0} &= \min\left[L_1 - c_1; L_2 - c_2\right] - \kappa \\ Q_1^{b0} &= 1 \\ S^{b0} &= 0. \end{aligned}$$

It is worth mentioning that these various equilibrium solutions have intersecting condition domains so that the pipeline company will choose the best solution among the feasible ones. It can be shown that, for the pipeline company, $l$ is always better than any other equilibrium solution if both are feasible, and that $b0$ is always worse than any other equilibrium if both are feasible, while $l0$ and $b$ are not comparable if both are feasible.

### 3.2.2 Numerical illustrations

Table 1 presents one illustrative example where all four possible equilibria are feasible. In that case, the pipeline company will set its price so that the distribution companies will not use the entire capacity in the first season, and will use the storage facility (case $l$ in the first column). The parameter values in this illustrative example represent a plausible situation, where the demand is relatively sensitive to price (Figure 2), where the high season accounts for around 60% of the total demand, and where the capacity of the pipeline is 130 Bcf per season, corresponding approximately to 20% of the demand for natural gas in Eastern Canada.[1] Equilibrium prices in the downstream market are then 3.78 ($8.22/Mcf) in Season 1 and 4.30 ($9.35/Mcf) in Season 2. Cost parameter values are chosen so that production costs are stable over the gas year, and transportation and distribution account for approximately 50% of the total cost (45% if storage is not used, 60% if storage is used).

Table 2 illustrates the impact of changes in the value of these parameters on the possible outcomes of the game. In order to allow comparisons, since changes in the demand function result in changes in the currency, prices and profits are reported in $/Mcf and $\$\times 10^6$ respectively, while volumes are reported in percentage pipeline capacity.

Case E0 is the base case of Table 1. Case E1 illustrates the impact of an increase in the number of downstream distribution firms, that is, an increase in the quantities marketed in both seasons, thus implying an increase in the quantity stored, lower prices, lower total profit in the downstream market, and higher profit for the pipeline company. Pipeline capacity becomes binding in the first season when the number of firms reaches 5. Increasing the number of firms further shifts the marketed quantities from Season 1 to Season 2, increasing storage and the profit of the pipeline company and decreasing the profit of the distribution companies. Case E2 illustrates the impact of a decrease in the slope of the demand function, which results in higher prices, lower quantities marketed in both seasons, and lower profits for both the transportation and distribution industry. Case E3 illustrates the impact of an increase in the seasonality, which results in a larger proportion of the production in Season 1 going to storage, with lower prices in both seasons, higher profit for the distribution companies, but lower profit for the pipeline company. Case E4 shows the impact of a decrease in the production cost, which results in an increase in the marketed quantities. When the production cost is small enough, as in Case E4, pipeline capacity becomes binding in the first season, prices are lower and industry profits are higher. Further decreases in the production cost have no impact on marketed quantities and prices, and only profit the pipeline company who increases the tariff accordingly. A reduction in the transportation cost has exactly the same impact as a reduction in the production cost. Finally, a change in the storage cost is directly reflected in tariff. As a consequence, quantities marketed in the first season do not change, and storage and total quantity increase (decrease) as a result of a cost decrease (increase). At some point, if the storage cost becomes very low, pipeline capacity becomes binding and production is transferred from demand satisfaction in Season 1 to Season 2. On the other hand, a very

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[1] Normalization of the capacity and demand function leads to the following unit conversion: 1 $u$ = 130 Bcf and 1\$/Mcf=0.46 $\mathcal{S}/u$.

large storage cost will eventually result in what is illustrated in Case E5, where capacity is not binding but storage is not used. This results in lower quantities and higher prices in the second season, which profit the distribution companies but is detrimental to the pipeline company.

Table 1: A case where all equilibria are feasible

| | $l$ | $l0$ | $b$ | $b0$ |
|---|---|---|---|---|
| $g$ | 2.525 | 2.525 | 2.475 | 1.55 |
| $f$ | 0.15 | 1.525 | 0.15 | 2.5 |
| $Q$ | 0.22 | 0.22 | 0.26 | 1 |
| $S$ | 0.7 | 0 | 0.74 | 0 |
| Profit pipeline | 2.473 | 1.8605 | 2.469 | 1.1 |
| $P_1$ | 3.78 | 3.78 | 3.74 | 3 |
| $P_2$ | 4.3 | 5 | 4.26 | 5 |
| Profit distribution | 0.8846 | 1.2871 | 0.9238 | 2.5 |

**Values of the parameters are:** $n = 4$, $L_1 = 4$, $L_2 = 6$, $c_1 = c_2 = 1.2$, $r = 1$, $a = 0.8$.

Table 2: Illustrative examples

| | E0($l$) | E1($b$) | E2($l$) | E3($l$) | E4($b0$) | E5($l0$) |
|---|---|---|---|---|---|---|
| Parameter changes | | $n = 6$ | $L_1$=3.48 | $L_1$=3.5 | $c_1 = 1$ | $a = 3$ |
| | | | $L_2 = 5.22$ | $L_2 = 6.5$ | $c_2 = 1$ | |
| $Q(u)$ | 0.22 | 0.243 | 0.012 | 0.02 | 0.26 | 0.22 |
| $S(u)$ | 0.7 | 0.757 | 0.388 | 0.9 | 0.74 | 0 |
| $P_1$($/Mcf) | 8.22 | 8.17 | 9.08 | 6.82 | 8.13 | 8.22 |
| $P_2$($/Mcf) | 9.35 | 9.22 | 10.03 | 9.02 | 9.26 | 10.87 |
| Profit pipeline (M $) | 699 | 736 | 500 | 590 | 811 | 526 |
| Profit distribution (M $) | 250 | 214 | 171 | 396 | 261 | 364 |

**Values of the parameters are as in Table 1 except otherwise indicated.**

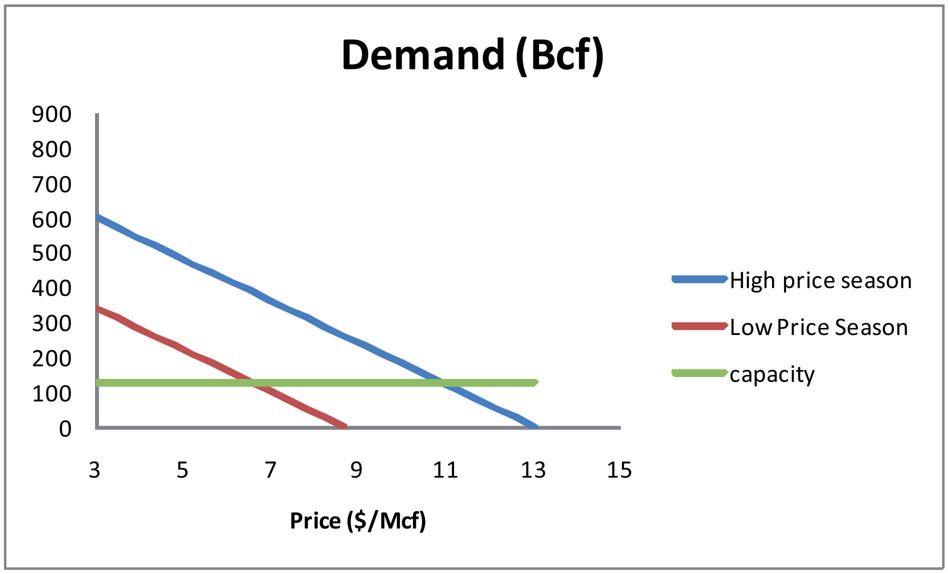

Figure 2: Demand function for the illustrative example in Table 1

### 3.2.3 Access fees after regulation

We now assume that the situation before regulation is such that situation $l$ is feasible; therefore, the pipeline company is setting its prices so that storage is used by the downstream market, and there is excess capacity in the first season. We study the effect on the industry of imposing a price cap $\theta < 1$ during a single year. Now, using (1), we denote

$$\begin{aligned} w_0 &= \frac{Q_1^- + 1}{R^-} \\ w_2 &= \frac{S^-}{R^-} \\ w_1 &= w_0 + w_2 \\ R^- &= g^- \left(Q_1^- + 1 + S^-\right) + f^- S^- \end{aligned}$$

where the superscript $^-$ indicates prices, quantities and revenues realized in the previous year. The price cap constraint in tariff basket PCR consists in requiring that access prices in the current year be such that the total revenue corresponding to the quantities of the previous year is reduced by at least $1 - \theta$ :

$$fS^- + g\left(Q_1^- + 1 + S^-\right) \leq \theta\left(f^- S^- + g^-\left(Q_1^- + 1 + S^-\right)\right).$$

Notice that $0 < w_2 < w_0 < w_1$.

In order to simplify the notation further, denote:

$$\begin{aligned} G &\equiv \frac{A + \kappa - r}{2} \\ H &\equiv \frac{B - \kappa - r - a}{2}, \end{aligned}$$

yielding

$$\begin{aligned} g^l &= r + G, \\ f^l &= a + H - G \\ Q_1^l &= \frac{G}{\kappa} - 1 \\ S^l &= \frac{H}{\kappa} \\ w_0 &= \frac{G}{\kappa R'} \\ w_2 &= \frac{H}{\kappa R'} \\ R^l &= \frac{1}{\kappa}\left(Ha + Gr + Hr + G^2 + H^2\right). \end{aligned}$$

Notice that when pipeline capacity is not binding in the first season, and when there is no regulation, the quantity distributed and stored are, in equilibrium, in proportion $\frac{Q_1^l + 1 + S}{S^l} = \frac{G + H}{H}$, and as a consequence, the weights compare as $\frac{w_0}{w_2} = \frac{G}{H}$.

With $\theta < 1$, if the prices and quantities in the previous period were in equilibrium, the price cap constraint will be active, and the optimization problem for the pipeline company is written:

$$\max_{g,f} \Pi_0 = (g - r)T(g, f) + (f - a)S(g, f) \tag{12}$$

s.t.

$$\left(w_0 + w_2\right) g + w_2 f = \theta$$

where we assume that

$$S(g, f) = \frac{B - g - f - \kappa}{\kappa} \tag{13}$$

$$
\begin{aligned}
&= \frac{2H + a + r - f - g}{\kappa} > 0 \\
T(g,f) &= \frac{A-g}{\kappa} + 1 + S(g,f) \qquad (14)\\
&= \frac{2G + 2H + a + 2r - f - 2g}{\kappa} < 2,
\end{aligned}
$$

that is, the total quantities sold and stocked, obtained from the reaction functions in the downstream market, will be such that storage is used and pipeline capacity is not binding during the first season.

Replacing in (12) yields a concave function which is optimized at

$$
\begin{aligned}
f^{\theta} &= \frac{-\left(w_0 + w_2\right) Z + 2\theta \left(w_2 - w_0\right)}{2\left(w_2^2 + w_0^2\right)} \\
g^{\theta} &= \frac{w_2 Z + 2 w_0 \theta}{2\left(w_2^2 + w_0^2\right)} \\
\text{where } Z &= 2 w_2 \left(r + G\right) - 2 w_0 \left(a + r + H\right).
\end{aligned}
$$

Using the weight factor values yields

$$
\begin{aligned}
f^{\theta} &= \frac{\left(G+H\right)\left(Ga + Gr - Hr\right) - \theta\left(G-H\right)\left(Ha + Gr + Hr + G^2 + H^2\right)}{G^2 + H^2} \\
&= f^{l} + \left(1-\theta\right)\kappa R^{l} \frac{G-H}{G^2+H^2} \\
g^{\theta} &= \frac{H\left(Hr - Ga - Gr\right) + G\theta\left(Ha + Gr + Hr + G^2 + H^2\right)}{G^2 + H^2} \\
&= g^{l} - \left(1-\theta\right)\kappa R^{l} \frac{G}{G^2+H^2}
\end{aligned}
$$

or equivalently:

$$
\begin{aligned}
\Delta_f &= f^{\theta} - f^{l} = \left(1-\theta\right)\frac{w_0 - w_2}{w_2^2 + w_0^2} \\
\Delta_g &= -g^{\theta} + g^{l} = \left(1-\theta\right)\frac{w_0}{w_2^2 + w_0^2}.
\end{aligned}
$$

Now, recall that under the weighting mechanism (2)–(3), because storage during a given period is bounded by the pipeline capacity, it is always the case that $w_2 < w_0$. Moreover, since we assumed positive storage before regulation, then we also have $w_2 > 0$. As a consequence, the adjustment $\Delta_g$ and $\Delta_f$ resulting from the imposition of a price cap $\theta < 1$ satisfies

$$
\begin{aligned}
\Delta_g &> \Delta_f > 0 \\
\frac{\Delta_g}{\Delta_f} &= \frac{G}{G-H}.
\end{aligned}
$$

The corresponding equilibrium is given by

$$
Q_1^{\theta} = Q_1^{l} + \frac{\Delta_g}{\kappa} \qquad (15)
$$

$$
S^{\theta} = S^{l} + \frac{\Delta_g - \Delta_f}{\kappa}. \qquad (16)
$$

and therefore, using (15)–(16), both the quantity delivered during the first season and the quantity stored for future delivery in the second season strictly increase at equilibrium as a consequence of the price cap.

The above results are valid provided that the new prices $g^{\theta}$ and $f^{\theta}$ satisfy the conditions for the equilibrium in the downstream market assumed in equations (13) and (14). These conditions are stated in (32)–(35). Since $f$, $S$ and $Q_1$ are increasing, conditions (32)–(34) are still satisfied. On the other hand, since both storage and quantity sold in the first season are increasing, the capacity constraint in the first period (35) becomes tighter. Assuming $Q_1^{\theta} + S^{\theta} < 1$, that is, full capacity is not yet attained following the imposition of a price cap, then the impact of this price cap on the industry equilibrium is the following:

1. **The ratio of storage to transport does not change**
   This property is shown in C. This is an interesting result: the imposition of a price cap limits the revenue of the pipeline owner, and in order to satisfy the cap, it is optimal for him to change the tariffs in a way that will lead the downstream companies to keep the quantities transported and stored in the same proportion. There is indeed an optimal ratio of storage to transportation for the pipeline owner if pipeline capacity is not binding in the first season, and this optimal ratio is equal to $\frac{H}{G+H}$.
2. **Price for the pipeline access decreases, price of storage increases**
   It suffices to observe that $\Delta_g$ and $\Delta_f$ are both positive. Notice that the decrease in the tariff for the pipeline access is larger than the increase in the price of storage.
3. **In the first season, supply increases and market price decreases**
   It suffices to observe that $\Delta_g$ is positive, so that the quantity distributed increases. Price decreases because of the increase in supply.
4. **In the second season, supply increases and market price decreases**
   It suffices to observe that $\Delta_g - \Delta_f$ is positive, so that the quantity stored for distribution during the second season increases. Price decreases because of the increase in supply.
5. **Profit of the pipeline company decreases**
   Profit decreases because an active constraint is added to the optimization problem of the pipeline company. The price cap constraint is always active for $\theta < 1$. The decrease in the profit of the pipeline company is
   $$\left(R^l\right)^2 \frac{(1-\theta)^2}{\kappa\left(G^2+H^2\right)}.$$
   Notice that it may however happen that the revenues of the pipeline owner actually increase as a result of the price cap.
6. **Profit in the downstream market increases**
   This property is shown in C. Profit from sales in the first season, from sales in the second season of the quantity contracted during the second season, and from sales in the second season of the quantity contracted during the first season and stored are all increasing with the imposition of a price cap. The total increase in profit in the downstream market is
   $$(1-\theta) R^l \frac{\kappa(2-\kappa)(G-H)+2(\kappa-1)\left(G^2+H^2\right)+(1-\theta) R^l \kappa(\kappa-1)}{\kappa\left(G^2+H^2\right)}.$$
7. **Consumer surplus increases**
   This is obvious from the fact that quantities marketed in both seasons increase, while prices in both seasons decrease. The increase in consumer surplus is
   $$\frac{1}{2} R^l (1-\theta) \frac{\kappa R^l (1-\theta)+2G(G-\kappa)+2H(H+\kappa)}{\kappa\left(G^2+H^2\right)}.$$
8. **Industry profit increases**
   This property is shown in C. The increase in the profit of the downstream market is always strictly larger than the decrease in the profit of the pipeline company, so that the industry profit is increasing with the imposition of a price cap. As a consequence, obviously, the imposition of a price cap increases the total surplus.

Finally, notice that if the unit transportation cost decreases by $\Delta_g$ and the unit storage cost increases by $\Delta_f$, then the equilibrium without regulation will be exactly the same as the one resulting from the imposition of a price cap $\theta$, so that regulation by price cap in a given year has an impact equivalent to an increase/decrease in the operating cost of the pipeline and storage, or the imposition of a proportional tax.

## 4 Dynamic setting

We now consider a dynamic setting where Year 0 is the test year where the company is operating as a monopolist without any regulation constraints. In subsequent years, the company is allowed to set prices freely provided that a weighted index of those prices is less than the price cap imposed by the regulator. We assume constant cap and cost parameters. Weights are adjusted dynamically on the basis of the revenues from the preceding year, as indicated in (1).

## 4.1 The myopic case

We first assume that the pipeline company is subject to a price cap constraint, but is not taking into account the impact of its pricing decisions on this constraint. This corresponds to a succession of static equilibria in each successive year.

### 4.1.1 Excess capacity in the first season

Again, we assume $\theta < 1$ and that pipeline capacity is not binding during the first low price season of year $t$, or equivalently (13)–(14) are satisfied in year $t$, so that the solution to the pipeline company's optimization problem is obtained as in the preceding section and given as a function of the weights by:

$$g_t^\theta = \frac{w_{2t} Z_t + 2 w_{0t} \theta}{2\left(w_{2t}^2 + w_{0t}^2\right)} \tag{17}$$

$$f_t^\theta = \frac{-\left(w_{0t} + w_{2t}\right) Z_t + 2\theta\left(w_{2t} - w_{0t}\right)}{2\left(w_{2t}^2 + w_{0t}^2\right)} \tag{18}$$

$$Z_t = 2 w_{2t}\left(r + G\right) - 2 w_{0t}\left(a + r + H\right). \tag{19}$$

**Proposition 1** *Assume conditions (8)–(11) are satisfied and Year 1 corresponds to the imposition of a price cap. Then the succession of myopic equilibria is given for* $t = 0, ..., t^*$ *by:*

$$\begin{aligned}
S_t^y &= S^l + \gamma_t \\
g_t^y &= g^l - \gamma_t \kappa \frac{G}{H} \\
f_t^y &= f^l + \kappa \gamma_t \frac{G-H}{H} \\
Q_t^y &= Q^l + \gamma_t \frac{G}{H} \\
\gamma_t &= \left(1 - \theta^t\right) \frac{HR}{G^2 + H^2} \\
\kappa R &= Ha + Gr + Hr + G^2 + H^2
\end{aligned}$$

*where* $t^* = \min\left\{t : Q_{t1}^y + S_t^y > 1\right\}$.

Proof of Proposition 1 is provided in D. The proof is by induction, relying on the results of the preceding section, which then correspond to the first year where a price cap is imposed. The implication of the above proposition is that the imposition of a constant price cap results in a regular increase of the quantities distributed and stored, as a result of a regular decrease in the price of the pipeline access and increase in the price of the storage, until full capacity is reached in the first season. Moreover, the ratio of the total quantity transported to the total quantity stored stays constant and equal to $\frac{G+H}{H}$.

Notice that a succession of price caps over the years have the same impact on access prices and quantities stored and distributed in a given year as imposing a single "compounded" price cap in this particular year. All results obtained in Section 3.2.3 directly apply, as long as excess pipeline capacity is still available in the first season. This last condition can be written as a limit for the compounded price caps as a function of the model parameters:

$$\theta^{t^*} > 1 + \frac{\left(G^2 + H^2\right)\left(G + H - 2\kappa\right)}{\kappa R\left(G + H\right)}.$$

### 4.1.2 Full pipeline capacity

As seen above, the imposition of a price cap eventually results in using the full capacity of the pipeline during the low price season. When this happens, the impact of imposing a price cap is no longer the same, given that the total quantity sold is maximal.

When pipeline capacity is binding, the demand for storage is:

$$S(g_t, f_t) = \frac{B - A - f_t}{2\kappa}.$$

The pipeline company then solves

$$\begin{aligned} \max_{g,f} \Pi_0 &= 2(g-r) + (f-a)\left(\frac{B-A-f}{2\kappa}\right) \\ \text{s.t.} & \\ & (w_{0t} + w_{2t})\, g + w_{2t} f = \theta \\ & A - \kappa\left(1 - \left(\frac{B-A-f}{2\kappa}\right)\right) - g \geq 0. \end{aligned}$$

The last constraint requires the multiplier for the capacity constraint in the downstream market optimization problem to be non-negative. Accordingly, there are two possible solutions for the pipeline company:

$$f_t^b = \frac{(w_{0t} + w_{2t})(B - A + a) - 4\kappa w_{2t}}{2(w_{0t} + w_{2t})} \tag{20}$$

$$g_t^b = \frac{1}{w_{2t} + w_{0t}}\left(\theta - w_{2t} f_t^b\right) \tag{21}$$

if

$$\frac{(A + B - 2\kappa)(w_{0t} + w_{2t}) - 2\theta}{(w_{0t} - w_{2t})} + 2\kappa \frac{w_{2t}}{w_{2t} + w_{0t}} + \frac{1}{2}(A - B - a) \geq 0, \tag{22}$$

otherwise:

$$f_t^l = \frac{(A + B - 2\kappa)(w_{0t} + w_{2t}) - 2\theta}{w_{0t} - w_{2t}} \tag{23}$$

$$g_t^l = \frac{1}{w_{2t} + w_{0t}}\left(\theta - w_{2t} f_t^l\right). \tag{24}$$

where solution (23)–(24) is obtained by setting the capacity constraint multiplier to 0.

Figure 3 illustrates the optimization problem faced by the pipeline company when it is operating at full capacity in the two above-mentioned situations. Access prices satisfy the price cap constraint $(w_{0t} + w_{2t})\, g + w_{2t} f = \theta$ and profits are plotted as a function of $f$. The solid line plots the profit of the pipeline when capacity is binding in the downstream market and the dotted line plots the profit when capacity is not binding. Capacity is binding to the left of the dashed vertical line and is not binding to the right of the dashed vertical line. In the left panel, the optimal solution is $f_t^l$ while in the right panel it is $f_t^b$.

When full capacity is attained, by continuity, the pipeline owner will fix his price according to (23)–(24) as long as condition (22) is not satisfied. This results in an increase in the access price for storage and a decrease in the quantity stored, until either storage vanishes or the capacity constraint becomes binding for the downstream market (this is shown in E).

When the capacity constraint becomes binding, storage is given by

$$\begin{aligned} S_t &= \frac{B - A - a}{4\kappa} + \frac{w_{2t}}{w_{0t} + w_{2t}} \\ &= \frac{B - A - a}{4\kappa} + \frac{S_{t-1}}{2} \end{aligned}$$

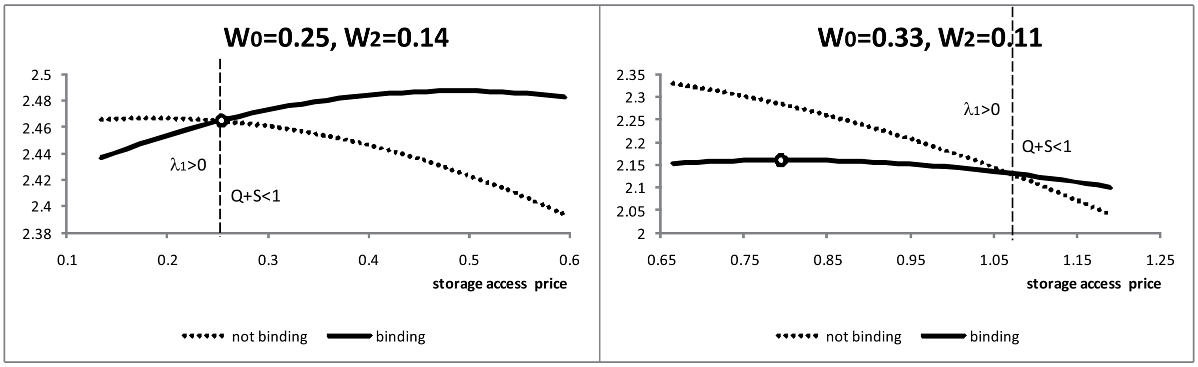

Figure 3: Pipeline optimization problem when capacity is entirely used in the low price period. Parameter values are as in Table 1 and $\theta = 0.995$. The optimal access price is 0.25 for the weights in the left panel and 0.80 for the weights in the right panel.

since total quantity transported is equal to 2. As a consequence, if $B - A - a < 0$, then storage decreases over time until it vanishes. On the other hand, if the unit cost of storage is smaller than the seasonal difference in prices, then a steady-state is attained at

$$\overline{S} = \frac{B - A - a}{2\kappa},$$

where quantities do not change anymore and storage access price is equal to the storage unit cost $a$. Price for pipeline access is adjusted according to (21) and decrease regularly over time.

In the long term, quantities stored are always less than before the imposition of the price cap. When storage does not vanish, the difference between quantities stored before and after PCR is:

$$\frac{B - a - r - \kappa}{2\kappa} - \frac{B - A - a}{2\kappa} = \frac{A - r - \kappa}{2\kappa} > 0.$$

On the other hand, the impact of a PCR is always an increase in the total quantities transported, up to the full capacity of the pipeline.

In summary, the impact of imposing a price cap after full capacity is attained is the following. Proofs are provided in E.

1. Storage decreases with time until it reaches a steady-state $\frac{B-A-a}{2\kappa}$ or vanishes if that value is negative. The decrease in storage is due to an increase by the pipeline owner of the storage access price. Since the pipeline is used at full capacity, the decrease in storage corresponds to a shift in the quantity distributed in the second season to the first season of the gas year.
2. Prices in the downstream market decrease during the low-price season and increase during the high-price season due to the shift in the marketed quantities.
3. Access prices for the pipeline continue to decrease to satisfy the price cap constraint. When storage stabilizes, pipeline tariff decreases while storage tariff no longer changes. This is due to the fact that storage demand only depends on the storage access price when capacity becomes binding.
4. Consumer surplus decreases as a result of the shift in the marketed quantities from the high-price season to the low-price season, until the steady-state is attained. In the long run, quantities marketed no longer change and consumer surplus is constant over time.
5. Profits in the downstream market increase over time. According to parameter values, total welfare can be increasing or decreasing in the period where the capacity is non binding, but in the long run total welfare becomes constant and pipeline profit decreases over time. This decrease in profit is then entirely captured by the distribution companies.

Combining the results of the two preceding sections, we see that price cap regulation results in an increase in the total welfare and consumer surplus, and a decrease in pipeline profit, as long as pipeline has excess

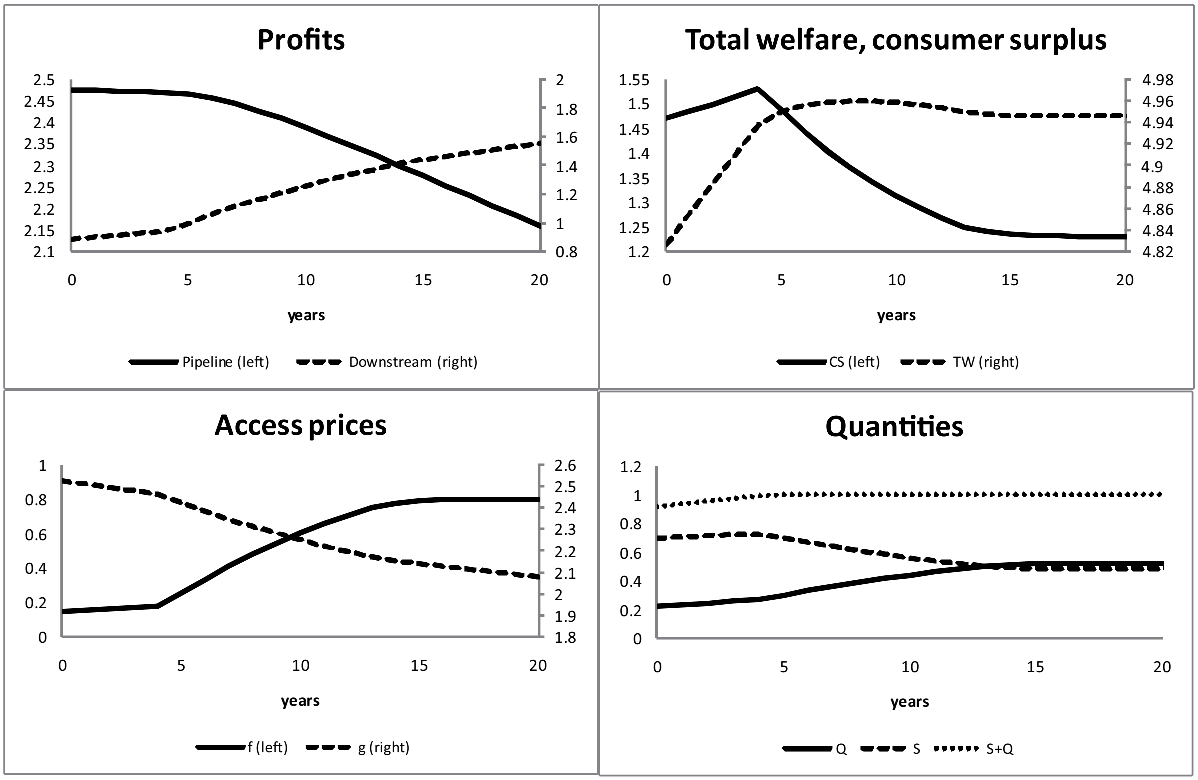

Figure 4: Parameter values are as in Table 1, with $\theta = 0.995$. Full capacity is attained in Year 5, capacity becomes binding in Year 13, steady-state is attained in Year 23.

capacity, but when capacity becomes binding, consumer surplus decreases while the distribution companies capture most of the benefits of the regulation. In fact, in the long run, it may happen that consumer surplus is lower with PCR than without regulation, as illustrated in Figure 4.

The impact of imposing a price cap over time is illustrated in Figures 4 and 5, where Year 0 corresponds to the situation before the imposition of a price cap. Figure 4 is an example of a case where storage stabilizes in the long run, while Figure 5 illustrates the case where storage is not used in the long run.

## 4.2 The dynamic equilibrium

From the results of the preceding sections, it is obvious that the profit of the pipeline company depends on the relative values of the weight factors $w_{0t}$ and $w_{2t}$, while these weight factors depend on the quantities transported and stored, and consequently on the pricing decisions, of the pipeline owner in the preceding years. Our aim in this section is to investigate whether the pipeline owner could gain by accounting for the impact of his pricing decisions on the future price cap constraints instead of behaving myopically in each successive year.

Assuming a constant $\theta$ over a finite horizon $T$, the optimization problem of the pipeline company is defined by the following dynamic program[2]:

$$v_t(w_0, w_2) = \max_{g,f} \{T(g,f)(g-r) + (f-a)\left(S(g,f)\right) + \beta v_{t+1}\left(w_0', w_2'\right)\} \tag{25}$$

where $\beta$ is the one-year discount factor and where weights are updated using (2)–(3), that is,

$$w_0' = \frac{T(g,f) - S(g,f)}{gT(g,f) + (f-a)S(g,f)}$$

---

[2] Price caps are often reset at the end of a five to ten years horizon. It is straightforward to adapt the formulation and numerical algorithm to any given schedule for the cap $\theta$, or to an infinite horizon.

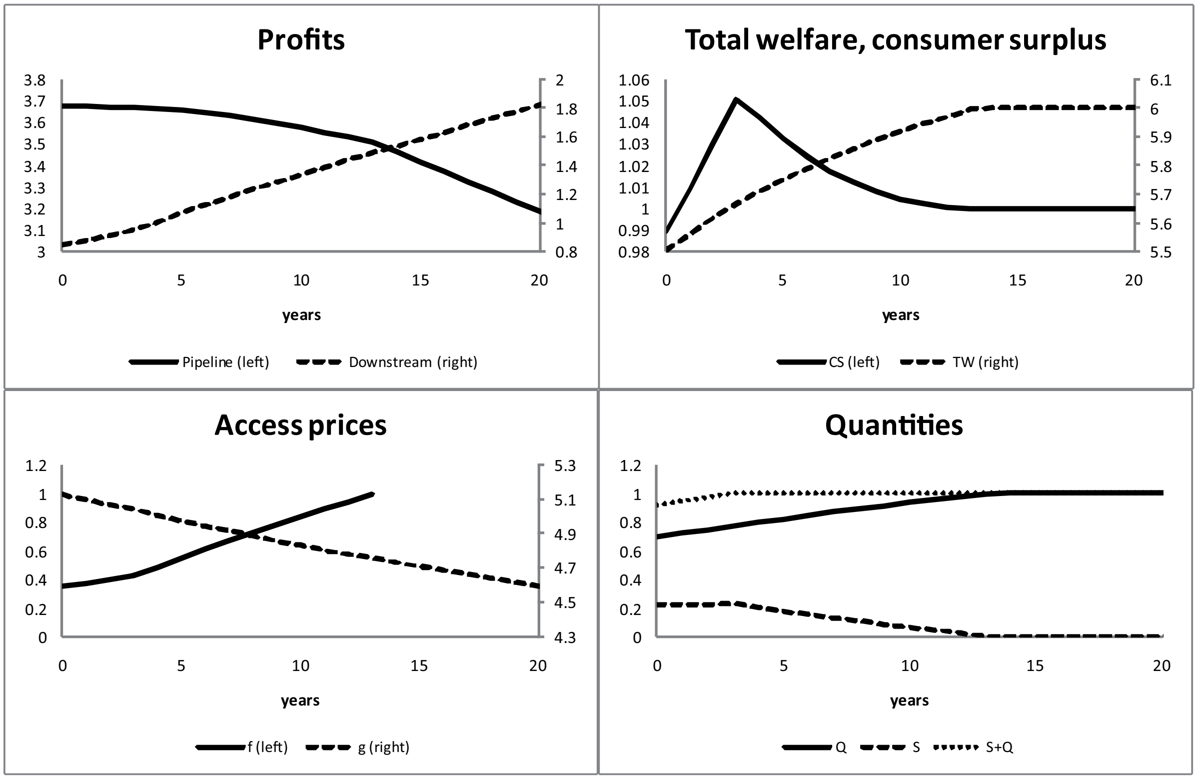

Figure 5: Parameters are $n$ =4, $L_1$ =9, $L_2$=10, $c_1 = c_2$=3, $r$ =3, $a$ =2.2, with $\theta = 0.995$. Full capacity is attained in Year 4 and storage vanishes in Year 14.

$$w_2' \quad = \quad \frac{S(g,f)}{gT(g,f) + (f-a)S(g,f)}.$$

According to the demand in the downstream market, two cases may arise if $w_2 > 0$:

1. Pipeline capacity not binding in the first season: In that case, demand is given by (4)–(5) and

$$\begin{aligned} T^l(g,f) &= \frac{A+B-f-2g}{\kappa} \\ S^l(g,f) &= \frac{B-f-g-\kappa}{\kappa}. \end{aligned}$$

   If a feasible solution exists at $(t, w_0, w_2)$, let

$$\begin{aligned} \left\{g^l, f^l\right\} \quad &= \quad \arg\max_{g,f} \left\{(g-r)T^l(g,f) + (f-a)S^l(g,f)\right. \\ &\qquad \left. + \beta v_{t+1}\left(w_0', w_2'\right)\right\} \\ \text{s.t.} & \\ &\quad f + g \le B - \kappa \\ &\quad A + B - f - 2g \le 2\kappa \\ &\quad 0 \le A - g \le 1 \\ &\quad \left(w_0 + w_2\right) g + w_2 f \le \theta \end{aligned}$$

   and denote

$$v_t^l(w_0, w_2) = (g^l - r)T^l(g^l, f^l) + (f^l - a)S(g^l, f^l) + \beta v\left(w_0', w_2'\right).$$

   If no feasible solution exists, set $v_t^l(w_0, w_2) = -\infty$.

2. Binding capacity in the first season: In that case, demand is given by (6)–(7) and

$$\begin{aligned} T^b(\cdot) &= 2 \\ S^b(f) &= \frac{B-A-f}{2\kappa}. \end{aligned}$$

If a feasible solution exists at $(t, w_0, w_2)$, let

$$\begin{aligned} \left\{g^b, f^b\right\} &= \arg\max_{g,f} \left\{2(g-r) + (f-a)S^b(f) + \beta v_{t+1}\left(w_0', w_2'\right)\right\} \\ \text{s.t.} & \\ & B - A - 2\kappa \leq f \leq B - A \\ & f + 2g \leq A + B - 2\kappa \\ & (w_0 + w_2)\, g + w_2 f \leq \theta \end{aligned}$$

and denote

$$v_t^b(w_0, w_2) = 2(g^b - r) + (f^b - a)S^b(f^b) + \beta v_{t+1}\left(w_0', w_2'\right).$$

If no feasible solution exists, set $v_t^b(w_0, w_2) = -\infty$.
We then have

$$v_t(w_0, w_2) = \max\left\{v_t^b(w_0, w_2); v_t^l(w_0, w_2)\right\}. \tag{26}$$

3. Finally, when $w_2 = 0$, storage is not used and the pipeline owner only has to decide on the pipeline tariff:

$$\begin{aligned} v_t(w_0, 0) &= \max_g \left\{\frac{(A - g + \kappa)}{\kappa}(g - r) + \beta v_{t+1}\left(\frac{1}{g}, 0\right)\right\} \\ \text{s.t.} & \\ & A - \kappa \leq g \leq A \\ & g \leq \frac{\theta}{w_0}. \end{aligned} \tag{27}$$

The above dynamic program does not admit a closed-form solution. Moreover, the state space is continuous. To obtain an approximation of the function $v$, define a partition of $[0, 1]$ into $(K + 1)$ intervals

$$[a_k, a_{k+1}) \quad \text{for } k = 0, \ldots, K \tag{28}$$

where $0 = a_0 \leq a_1 < \ldots < a_K < a_{K+1} = 1$ and a grid $\mathcal{G} = \{a_k\} \times \{a_k\}_{k=1,\ldots,K}$. The standard projection of the above dynamic program to a finite-state, infinite horizon Markov Decision Program is obtained by computing the projected value function $\widetilde{v}$ on grid $\mathcal{G}$, where each state corresponds to a grid point $(w_1, w_2) = (a_{k_1}, a_{k_2})$. Notice that to simplify notation, we assume that the partitions are identical for both sets of weights, but clearly this is not required (recall that $w_2 < w_0$).

A value iteration algorithm can then be used to solve equation (25), yielding the projected value function at each date $t$, as follows:

1. Initialization: set $t = T$ and $\widetilde{v}_{T+1}(k_1, k_2) = 0$ for $k_1, k_2 = 1, \ldots, K$.
2. Compute $\widetilde{v}_t(k_1, k_2)$ according to (26) or (27) for $k_1, k_2 = 1, \ldots, K$.
3. If $t = 0$, stop. Otherwise, set $t = t - 1$ and go to Step 2.

To extend the value function to weight pairs $(w_0', w_2')$ that are not grid points, an interpolation function is used. In our implementation, we used bilinear interpolation. Notice that our choice for $\widetilde{v}_{T+1}(\cdot)$ implies that the pipeline owner is using the myopic solution for the last year of the horizon.

## 4.3 Numerical results

Table 3 reports on various cases, with contrasting parameter values, for which we obtained the dynamic equilibrium using the algorithm outlined in the preceding section. Average grid precision for weights is 0.002, $\theta = 0.99$ and discount factor is $\beta = 0.9$. The last line indicates the percentage increase in total discounted profit over 10 years with respect to the myopic solution.

Figures 6 to 10 plot over an horizon of ten years the relative differences, with respect to the myopic case, in access prices and quantities marketed and stored. Case E0 is the base case discussed in Section 3.2.2. In the myopic case, full capacity is reached in Year 3, while in the dynamic case, storage price is higher during the first years, so that storage increases less rapidly and full capacity is reached later, in Year 4. However this strategic behavior results in a mere increase of 0.036% for the total discounted profit over the 10 year horizon. Case E1 corresponds to a situation where the demand in the downstream market is less sensitive to price. In both the myopic and dynamic cases, full capacity has not been reached by Year 10. Again, in the dynamic case, the pipeline owner sets a higher price for storage when there is excess capacity so that the total storage is lower and full capacity is reached later. In Case E2, seasonality is more important. In the dynamic equilibrium, storage price and quantities distributed during the low price season are larger than in the myopic case for the whole horizon, and full capacity is again reached one year later than in the myopic case. Case E3 is a situation where the cost of production is relatively higher than the cost of transportation and storage. Case E4 has low seasonality and high production, transportation and storage costs, so that storage vanishes by Year 7. In all these cases, accounting for the dynamics of the price cap translates into lower storage access fees during the first years, which is compensated by larger pipeline tariffs, and result in a slower increase in the volume stored over time and a longer period where excess capacity is available.

However we find that, in the range of feasible parameter values, the advantage for the pipeline company of behaving strategically is not very significant, as the impact on profit with respect to the myopic case

Table 3: Illustrative examples

| | $E0$ | $E1$ | $E2$ | $E3$ | $E4$ |
|---|---|---|---|---|---|
| $n$ | 4 | 4 | 4 | 4 | 4 |
| $L_1$ | 4 | 3.5 | 3.5 | 4 | 9 |
| $L_2$ | 6 | 5.5 | 6.5 | 6 | 10 |
| $c_1 = c_2$ | 1.2 | 1.2 | 1.2 | 2 | 3 |
| $r$ | 1 | 1 | 1 | 0.5 | 3 |
| $a$ | 0.8 | 0.8 | 0.8 | 0.5 | 2.2 |
| $\Delta\pi(\%)$ | 0.036 | 0.0017 | 0.0084 | 0.0081 | 0.0196 |

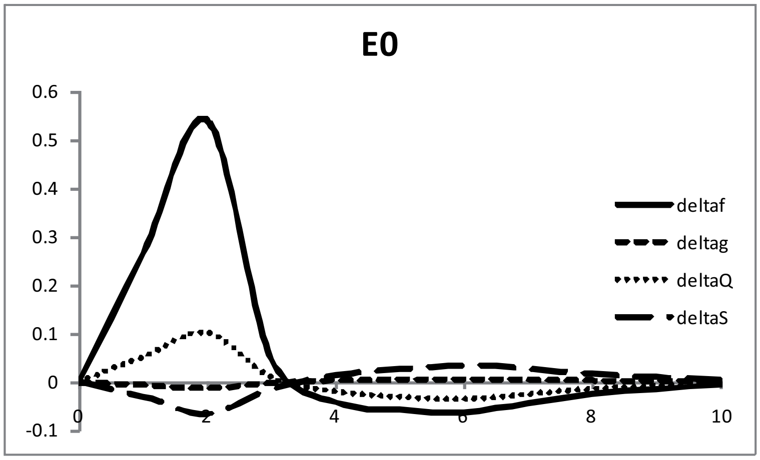

Figure 6: Example E0

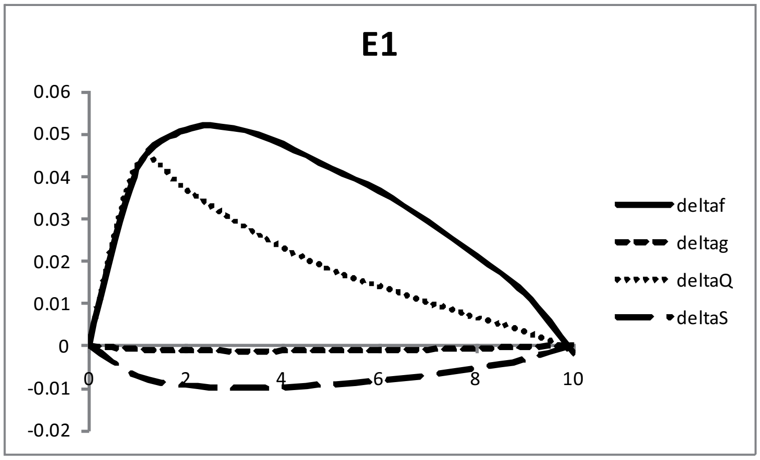

Figure 7: Example E1

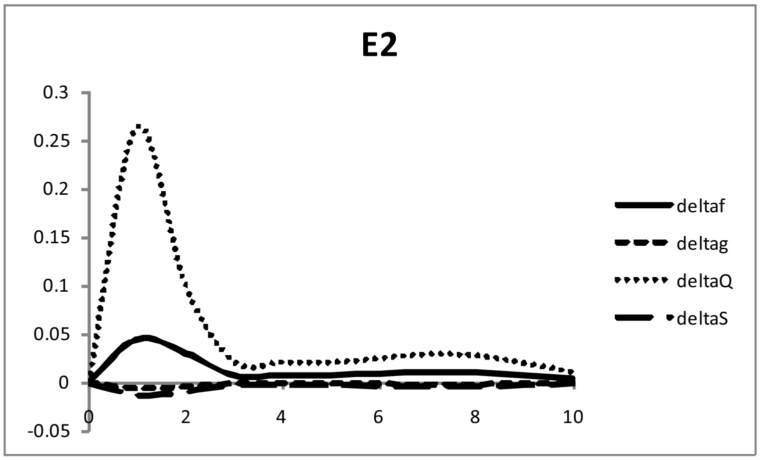

Figure 8: Example E2

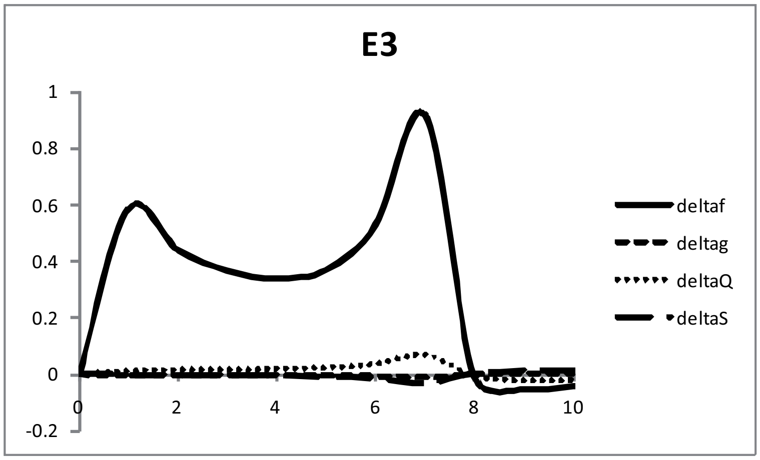

Figure 9: Example E3

is relatively small. Considering that, in practice, weights are rounded values, it seems that there is no real incentive for the pipeline owner to endogenize the changes in the price cap constraint over time. This outcome is due to the fact that the profit function of the regulated company is relatively flat in the region where the

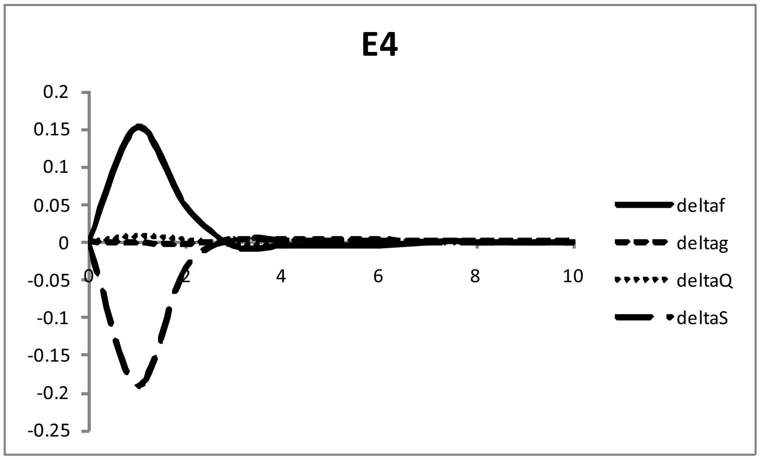

Figure 10: Example E4

weight factors are likely to observed if the access prices were optimal before regulation. In fact, the dynamic bi-level optimization problem faced by the pipeline owner is highly constrained, especially when the pipeline capacity is entirely used. It is worthwhile noticing that the basket price cap mechanism eventually results in binding pipeline capacity, relatively sooner when seasonality is high and when the cap is stringent.

## 5 Conclusion

Seasonal storage is used extensively in the gas industry. In many cases, gas production is fairly constant throughout the year, but seasonality in demand is high; gas is injected into storage during the low demand season, and withdrawn during the high demand season to bridge the seasonal gap between supply and demand and to benefit from higher selling prices. The use of storage facilities also allows local distribution companies to use contracted pipeline capacity at relatively stable rates during the gas year.

In this paper, we study the welfare effects of price cap regulation in the gas transportation and storage industry. Price cap regulation is one of the preferred mechanisms aimed at protecting consumers from monopolistic behavior in network industries. While many papers have analyzed the welfare effects of PCR, the interdependency and seasonality of demand for storage and transportation makes the specific problem of the gas industry different from the ones already studied in the literature. Moreover, the unbundling of sales from transportation and storage services results in a hierarchical game between the regulated pipeline company and the local distribution companies.

This paper models the optimization problem of the regulated company as a bi-level optimization problem, where the demand for transportation and storage access is derived from the oligopolistic equilibrium in the downstream distribution market. This allows to outline the impact of the capacity constraint on the reaction function of the distribution companies and on the optimal access prices. This is particularly relevant since most long-haul gas pipelines are used at capacity or near capacity.

Since price cap weight factors are adjusted yearly on the basis of the revenue of the regulated company, we analyze the impact of PCR on the access prices, marketed quantities, industry profits and consumer welfare in a dynamic setting. We consider both the case where prices are set myopically, and the case where the impact of pricing decisions on future weight factors is taken into account by the regulated company.

We find that, due to the direct link between the demand for pipeline access and storage, and to the capacity constraints, some results from the literature on PCR do not hold in our case. Indeed, when the capacity constraint is binding, the impact of a price cap is a reduction in consumer surplus, and benefits of the mechanism are essentially captured by the downstream distribution companies. Moreover, we find that the imposition of a price cap always results in a higher transportation volume, eventually resulting in a binding capacity constraint, and therefore in a decrease in consumer surplus. Examples with representative parameter values are provided where consumer surplus is lower after regulation than before regulation.

We also find that there is no significant advantage for the regulated company to set prices strategically in order to manipulate the price cap constraint.

It is worthy observing that one of the advantages identified with PCR is the incentives it gives companies to increase productivity and reduce costs; this particular effect of PCR is not taken into account in our setting, where productivity and costs are assumed constant over time. The price cap constraint is usually adjusted on a five years basis to account for changes in productivity and costs. It is interesting to note that strategic manipulations of the price cap constraint reported in the literature are related to this specific aspect. Notice that our results are derived assuming that the price cap constraint is constant over time to simplify the exposition; however, all results are valid for any price cap value, constant of not, provided that the cap is less than one.

One important aspect of the gas industry is the high uncertainty in the demand function. Indeed, demand for gas depends on prices of alternative energy sources and on climatic and economic conditions. Uncertain demand and prices make the storage facilities even more important as a means to allow the exercise of real options to postpone or increase distribution. Considering the impact of demand uncertainty on the value of storage for the distribution firm and on the pricing decisions of the regulated firm is an interesting extension, which is left for further research.

# A Downstream market, static case

In the downstream market, a distribution firm chooses the distribution and storage levels maximizing its total profits:

$$\max_{q_{mj}\geq 0, s_j\geq 0} \Pi_j = q_{1j}(P_1 - c_1 - g) + q_{2j}(P_2 - c_2 - g) + s_j(P_2 - c_1 - g - f) \tag{29}$$

where

$$\begin{array}{rcl} P_1 & = & L_1 - Q_1^{-j} - q_{1j} \\ P_2 & = & L_2 - Q_2^{-j} - q_{2j} - S^{-j} - s_j \\ 1 & \geq & q_{1j} + Q_1^{-j} + s_j + S^{-j} \\ 1 & \geq & q_{2j} + Q_2^{-j}. \end{array}$$

and where $Q_{tm}^{-j} = \sum_{i\neq j} q_{tmi}$ and $S_t^{-j} = \sum_{i\neq j} s_{ti}$. It is straightforward to check that individual profit functions are concave. Assuming that the second season capacity is binding, individual optimality conditions are thus given by:

$$\begin{array}{rcl} L_1 - Q_1^{-j} - 2q_{1j} - c_1 - g - \lambda_{1j} & \leq & 0, q_{1j} \geq 0 \\ q_{1j}\left(L_1 - Q_1^{-j} - 2q_{1j} - c_1 - g - \lambda_{1j}\right) & = & 0 \\ L_2 - Q_2^{-j} - 2q_{2j} - S^{-j} - 2s_j - c_2 - g - \lambda_{2j} & \leq & 0, q_{2j} \geq 0 \\ q_{2j}\left(L_2 - Q_2^{-j} - 2q_{2j} - S^{-j} - 2s_j - c_2 - g - \lambda_{2j}\right) & = & 0 \\ -2q_{2j} + L_2 - Q_2^{-j} - S^{-j} - 2s_j - c_1 - g - f - \lambda_{1j} & \leq & 0, s_j \geq 0 \\ s_j\left(-2q_{2j} + L_2 - Q_2^{-j} - S^{-j} - 2s_j - c_1 - g - f - \lambda_{1j}\right) & = & 0 \\ 1 - q_{1j} - Q_1^{-j} - s_j - S^{-j} & \geq & 0, \lambda_{1j} \geq 0 \\ \lambda_{1j}\left(1 - q_{1j} - Q_1^{-j} - s_j - S^{-j}\right) & = & 0 \\ q_{2j} + Q_2^{-j} & = & 1 \\ \lambda_{2j} & \geq & 0, \end{array}$$

where $\lambda_{jm}$ is the multiplier associated to the capacity constraint in season $m$. Assuming identical firms, positive quantities and binding capacity in the second season, the equilibrium productions and storage are obtained by simultaneously solving

$$\begin{aligned}
A - n\kappa q_1 - g &= \lambda_1 \\
L_2 - \kappa - n\kappa s - c_2 - g &= \lambda_2 \\
B - A - f - \kappa + n\kappa\,(q_1 - s) &\leq 0, s \geq 0 \\
s\,(B - A - f - \kappa + n\kappa\,(q_1 - s)) &= 0 \\
n\,(q_1 + s) &\leq 1, \lambda_1 \geq 0 \\
\lambda_1\,(1 - n\,(q_1 + s)) &= 0 \\
\lambda_2 &> 0.
\end{aligned}$$

Possible cases are the following:

1. $\lambda_1 = 0$, $s \geq 0$ yielding

$$\begin{aligned}
\lambda_2 &= c_1 + f - c_2 \\
s &= \frac{B - f - g - \kappa}{n\kappa} && (30) \\
q_1 &= \frac{A - g}{n\kappa} && (31)
\end{aligned}$$

where

$$\begin{aligned}
c_1 + f - c_2 &\geq 0 && (\text{cap}_2) && (32) \\
B - f - g - \kappa &\geq 0 && (s) && (33) \\
A - g &\geq 0 && (q_1) && (34) \\
A + B - f - 2g &\leq 2\kappa && (\text{cap}_1)\,. && (35)
\end{aligned}$$

2. $\lambda_1 = 0, s = 0$, yielding

$$\begin{aligned}
q_1 &= \frac{A - g}{n\kappa} \\
\lambda_2 &= B - \kappa + c_1 - c_2 - g
\end{aligned}$$

where

$$\begin{aligned}
0 &\leq A - g \leq \kappa && (q_1, \text{cap}_1) \\
B + c_1 - c_2 &\geq \kappa + g && (\text{cap}_2) \\
B &\leq \kappa + g + f && (s).
\end{aligned}$$

3. $\lambda_1 > 0, s > 0$, yielding

$$\begin{aligned}
q_1 &= \frac{A - B + f + 2\kappa}{2n\kappa} \\
s &= \frac{B - A - f}{2n\kappa} \\
\lambda_1 &= \frac{1}{2}(A + B - f) - g - \kappa \\
\lambda_2 &= \frac{1}{2}(A + B + f) - g - \kappa + c_1 - c_2
\end{aligned}$$

where

$$\begin{aligned}
A - B + f + 2\kappa &\geq 0 && (q_1) \\
B - A - f &\geq 0 && (s) \\
A + B - f - 2g - 2\kappa &\geq 0 && (\lambda_1) \\
A + B + f - 2g - 2\kappa + 2\,(c_1 - c_2) &\geq 0 && (\lambda_2)
\end{aligned}$$

4. $\lambda_1 > 0, s = 0$, yielding

$$\begin{aligned} q_1 &= \frac{1}{n} \\ \lambda_1 &= A - g - \kappa \\ \lambda_2 &= -g - \kappa + B + c_1 - c_2 \end{aligned}$$

where

$$\begin{aligned} A - g - \kappa &> 0 \qquad (\lambda_1) \\ -g - \kappa + B + c_1 - c_2 &> 0 \qquad (\lambda_2) \\ B - A - f &< 0 \qquad (s)\,. \end{aligned}$$

# B Transportation and storage access fees before regulation

1. **Capacity constraint not binding in the first season with storage**

The profit of the pipeline company is written:

$$\begin{aligned} \Pi_0(g, f) &= (g - r)\left(\left(\frac{A - g}{\kappa}\right) + 1 + \left(\frac{B - g - f - \kappa}{\kappa}\right)\right) \\ &\quad +(f - a)\left(\frac{B - g - f}{\kappa} - 1\right). \end{aligned}$$

This is a concave function, and the optimal prices for the pipeline company are given by solving for the first order conditions:

$$\begin{aligned} g^l &= \frac{1}{2}(A + r + \kappa)\,, \\ f^l &= \frac{1}{2}(B - A + a - 2\kappa)\,. \end{aligned}$$

The corresponding downstream equilibrium is then obtained by replacing these values in (30-31)

$$\begin{aligned} Q_1^l &= \frac{1}{2\kappa}(A - r - \kappa) \\ S^l &= \frac{1}{2\kappa}(B - r - a - \kappa)\,, \end{aligned}$$

which can be shown to yield positive prices in the downstream market if $L_2 > 1$. Total profit for the pipeline company can then be written as a function of the model parameters:

$$\Pi_0^l = \frac{1}{4\kappa}\left((A - r + \kappa)^2 + (B - r - a - \kappa)^2\right) \geq 0.$$

This solution is feasible if the following conditions are satisfied:

$$\begin{aligned} B - r - a &> \kappa \qquad (36) \\ A + B - a - 2r &\leq 4\kappa, \qquad (37) \end{aligned}$$

(36) corresponding to the assumption of positive storage and (37) to the assumption of non binding capacity in the first season. It can be checked that the assumptions of positive quantities during the first season and binding capacity during the second season are equivalent to conditions (8) and (9) respectively. Notice that under these conditions, $g^l \geq r + \kappa$ and $f^l \leq a$. Thus, margin from the pipeline operation is positive, but margin from the storage operation is negative, and it could even be advantageous for the pipeline company to subsidize storage in order to increase demand, with $f^l < 0$.

2. **Capacity constraint not binding in the first season, no storage**
The profit of the pipeline company is now written:

$$\Pi_0(g,f) = (g-r)\left(\left(\frac{A-g}{\kappa}\right)+1\right).$$

Straightforward computations yield:

$$\begin{aligned} g^{l0} &= \frac{1}{2}(A+r+\kappa) \\ Q_1^{l0} &= \frac{1}{2\kappa}(A-r-\kappa), \end{aligned}$$

and the total profit for the pipeline company is then:

$$\Pi_0^{l0} = \frac{1}{4\kappa}\left((A-r+\kappa)^2\right) > 0$$

if the following conditions are satisfied:

$$\begin{aligned} A-r &\leq 3\kappa && (38) \\ f^{l0} &\geq B-\frac{1}{2}(A+r+3\kappa). && (39) \end{aligned}$$

The prices in the downstream market are positive if $L_2 > 1$.The condition for positive quantity during the first season and full pipeline capacity in the second season are respectively equivalent to (8) and (10). Condition (38) ensures that capacity is not binding in the first season, while (39) is the condition ensuring that there is no storage, that is, the price for storage is sufficiently high.

3. **Capacity constraint binding in the first season with storage**:
The profit of the pipeline company is written:

$$\Pi_0(g,f) = 2(g-r)+(f-a)\frac{(B-A-f)}{2\kappa}.$$

This function is linear increasing in $g$ and concave in $f$. For any given $f$, increasing $g$ decreases the value of the multiplier for the capacity constraint in the first season, so that the optimal solution for the pipeline company is such that

$$\lambda_1^b = \frac{1}{2}(A+B-f-2g-2\kappa) = 0,$$

yielding

$$g^b = \frac{1}{2}(A+B-f)-\kappa.$$

Replacing in the profit function yields a concave function in $f$, which attains its maximum value at :

$$\begin{aligned} f^b &= f^l = \frac{1}{2}(B-A+a)-\kappa \\ g^b &= \frac{1}{4}(3A+B-a-2\kappa). \end{aligned}$$

The corresponding downstream equilibrium is then

$$\begin{aligned} Q_1^b &= \frac{1}{2}+\frac{a-B+A}{4\kappa} \\ S^b &= \left(\frac{1}{2}-\frac{a-B+A}{4\kappa}\right), \end{aligned}$$

which can be shown to yield positive prices in the downstream market under conditions (8), (9) and (40). Total profit for the pipeline company can then be written as a function of the model parameters:

$$\Pi_0^b = \frac{1}{8\kappa}\left((A-B+a)+6\kappa\right)^2+2(B-a-r)-6\kappa.$$

Now it can be shown that under conditions (8) and (40), total profit is non negative and that condition (11) is equivalent to the assumption of positive quantity in the first season, while condition (9) ensures that capacity is binding in the second season. This solution is feasible if the following condition is satisfied:

$$B - A - a > -2\kappa, \tag{40}$$

corresponding to the assumption of positive storage in the downstream market.

4. **Capacity constraint binding in the first season, no storage**

   In that case the profit of the pipeline company becomes linear in $g$. The optimal solution is thus obtained by inspection of the optimality conditions and is given by:

$$\begin{aligned} f^{b0} &\geq B - A \\ g^{b0} &= \min\left[A; B + c_1 - c_2\right] - \kappa \\ Q_1^{b0} &= 1 \\ S^{b0} &= 0 \\ \Pi_0^{b0} &= 2(g^{b0} - r), \end{aligned}$$

   where it is easy to show that $\Pi_0^{b0}$ is non negative under (8) and (10).

# C Impact of price cap

Denote $\gamma$ the increase in stored quantities as a result of the imposition of a price cap,

$$\gamma = (1-\theta)\,\frac{HR}{G^2 + H^2}.$$

We then have

$$\begin{aligned} \Delta_f &= \kappa\gamma\frac{G-H}{H} \\ \Delta_g &= \frac{G}{H}\kappa\gamma \\ \Delta_Q &= \frac{G}{H}\gamma \end{aligned}$$

**Ratio of storage to transport**

Before regulation, $\frac{Q_1^l+1}{S^l} = \frac{G}{H}$. After regulation,

$$\begin{aligned} \frac{Q_1^\theta + 1}{S^\theta} &= \frac{Q_1^l + 1 + \frac{G}{H}\gamma}{S^l + \gamma} \\ &= \frac{\frac{S^l G}{H} + \frac{G}{H}\gamma}{S^l + \gamma} \\ &= \frac{G}{H}. \end{aligned}$$

The ratio of storage to transport, before and after the price cap regulation, is therefore constant and equal to $\frac{S}{Q+1+S} = \frac{H}{G+H}$.

**Profit in the downstream market**

Profit in the downstream market is given by:

$$Q_1(A - Q_1 - g) + (B - 1 - S + c_1 - c_2 - g) + S(B - 1 - S - g - f)$$

so that the increase in profit after regulation is:

$$\Delta_Q\left(A - Q_1^l - g^l\right) + \left(Q_1^l + \Delta_Q\right)\left(-\Delta_Q + \Delta_g\right)$$

$$\begin{aligned}&-\Delta_S + \Delta_g \\ &+\Delta_S \left(B - 1 - S^l - g^l - f^l\right) + \left(S^l + \Delta_S\right)\left(-\Delta_S + \Delta_g - \Delta_f\right).\end{aligned}$$

The first term is the increase in profit during the first season, the second term is the increase in profit in the second season from the quantity contracted during the second season and the third term is the increase in profit from the quantity contracted during the first season and stored for distribution during the second season.

Replacing the values $Q_1^l = \frac{G}{\kappa} - 1$, $S^l = \frac{H}{\kappa}$, $g^l = r + G$, $f^l = a + H - G$, $A = 2G + r - \kappa$, $B = 2H + a + r + \kappa$ and rearranging yields the following expression for each term in the increase in profit:

$$\begin{aligned}&G\gamma\left(\kappa - 1\right)\frac{2H\left(G - \kappa\right) + G\kappa\gamma}{H^2\kappa} \\ &+\gamma\frac{-H + G\kappa}{H} \\ &+\gamma\left(\kappa - 1\right)\frac{2H + \kappa + \kappa\gamma}{\kappa}.\end{aligned}$$

Using $0 \leq Q_1^l \leq 1$ and $0 \leq S^l \leq 1$ yields

$$0 \leq H \leq \kappa \leq G \leq 2\kappa$$

where $1 < \kappa < 2$. As a consequence, all three terms are positive and profit in the downstream market is increasing in both seasons. Total profit increase is given by:

$$\gamma\frac{H\left(\kappa\left(2 - \kappa\right)\left(G - H\right) + 2\left(G^2 + H^2\right)\left(\kappa - 1\right)\right) + \kappa\gamma\left(G^2 + H^2\right)\left(\kappa - 1\right)}{H^2\kappa}. \tag{41}$$

**Consumer surplus**

Consumer surplus is given by:

$$\frac{Q_1^2}{2} + \frac{(1 + S)^2}{2},$$

so that the increase in consumer surplus is:

$$\begin{aligned}&\frac{1}{2}\left(\Delta_Q\left(2Q_1^l + \Delta_Q\right) + \Delta_S\left(2S^l + \Delta_S + 2\right)\right) \\ =\ &\frac{1}{2}\gamma\frac{2H\left(G\left(G - \kappa\right) + H\left(H + \kappa\right)\right) + \kappa\gamma\left(G^2 + H^2\right)}{H^2\kappa}\end{aligned}$$

**Profit of the pipeline company**

Profit of the pipeline company is given by:

$$(g - r)(Q_1 + S + 1) + (f - a)S$$

so that the decrease in the profit of the pipeline company is :

$$\begin{aligned}&\Delta_g\left(Q_1^l + \Delta_Q + S^l + \Delta_S + 1\right) - \Delta_f\left(S^l + \Delta_S\right) - \Delta_S\left(g^l - r + f^l - a\right) - \Delta_Q\left(g^l - r\right) \\ =\ &G\gamma\left(H + \kappa\gamma\right)\frac{G + H}{H^2} \\ &-\gamma\left(H + \kappa\gamma\right)\frac{G - H}{H} \\ &-H\gamma \\ &-G^2\frac{\gamma}{H} \\ =\ &\kappa\gamma^2\frac{G^2 + H^2}{H^2}.\end{aligned} \tag{42}$$

**Industry profit**

The difference between the increase in the downstream companies profit increase and the pipeline company profit decrease, using (41)–(42), is given by:

$$\begin{aligned}
& \gamma\frac{H\left(\kappa\left(2-\kappa\right)\left(G-H\right)+2\left(G^2+H^2\right)\left(\kappa-1\right)\right)+\kappa\gamma\left(G^2+H^2\right)\left(\kappa-1\right)}{H^2\kappa} \\
& -\kappa\gamma^2\frac{G^2+H^2}{H^2} \\
= \ & \gamma\frac{H\left(\kappa\left(2-\kappa\right)\left(G-H\right)+2\left(G^2+H^2\right)\left(\kappa-1\right)\right)-\kappa\gamma\left(G^2+H^2\right)}{H^2\kappa} \qquad (43)
\end{aligned}$$

Now, this solution is feasible if the quantities transported and stored after the imposition of the price cap satisfy the capacity constraint, that is:

$$\frac{G}{\kappa}-1+\frac{G}{H}\gamma+\frac{H}{\kappa}+\gamma<1$$

from which we retrieve the condition

$$\kappa\gamma\left(G^2+H^2\right)<H\left(G^2+H^2\right)\frac{2\kappa-G-H}{G+H}.$$

Accordingly, the numerator in (43) satisfies

$$\begin{aligned}
& H\left(\kappa\left(2-\kappa\right)\left(G-H\right)+2\left(G^2+H^2\right)\left(\kappa-1\right)\right)-\kappa\gamma\left(G^2+H^2\right) \\
> \ & H\left(\kappa\left(2-\kappa\right)\left(G-H\right)+2\left(G^2+H^2\right)\left(\kappa-1\right)\right)-\frac{H\left(G^2+H^2\right)\left(2\kappa-G-H\right)}{\left(G+H\right)} \\
= \ & H\left(\kappa-1\right)\frac{GH^2+G^2H+H^2\kappa+G^3}{G+H}+HG^2\kappa\frac{G-\kappa}{G+H} \\
& +H^2\frac{H^2\left(\kappa-1\right)+\kappa\left(\left(G-H\right)^2+3H\left(G-1\right)\right)}{G+H}
\end{aligned}$$

which is strictly positive since $G>\kappa>1$.

# D Proof of Proposition 1

The proof is by induction. We already have shown that the proposition is true for $t=1$, with

$$\begin{aligned}
w_{01} &= \frac{G}{\kappa R} \\
w_{21} &= \frac{H}{\kappa R}.
\end{aligned}$$

Assume that the proposition is true at $t-1$, $t\geq 2$. This implies that the weights at $t$ satisfy

$$\begin{aligned}
w_{2t} &= \frac{H}{\theta^{t-1}R\kappa} \\
w_{0t} &= \frac{G}{\theta^{t-1}R\kappa}.
\end{aligned}$$

It suffices to replace these values in (17)–(18) to obtain

$$\begin{aligned}
g_t^{\theta} &= G+r-R\kappa\left(1-\theta^t\right)\frac{G}{G^2+H^2} \\
f_t^{\theta} &= H-G+a+R\kappa\left(1-\theta^t\right)\frac{G-H}{G^2+H^2}.
\end{aligned}$$

provided the corresponding quantities satisfy the capacity constraint. ☐

# E Impact of price cap at full capacity

### Quantities and access prices

We first check the impact of the price cap when the capacity constraint is not binding in the downstream market while there is no excess capacity. This is the situation starting from the first year where the solution computed in Section 4.1.1 is no longer feasible, provided the condition (22) is not satisfied. We then have:

$$\begin{aligned} S &= \frac{B-g-f-\kappa}{\kappa} \\ 1 &= \frac{B-g-f-\kappa}{\kappa} + \frac{A-g}{\kappa} \end{aligned}$$

from which we get

$$\begin{aligned} f &= B-A-2S\kappa \qquad (44) \\ g &= \frac{1}{2}A+\frac{1}{2}B-\frac{1}{2}f-\kappa \\ &= A-\kappa+S\kappa. \qquad (45) \end{aligned}$$

Denote $S^{-}, f^{-}$ and $g^{-}$ the storage and access prices in the preceding year. The price cap constraint consists in requiring that

$$fS^{-}+2g=\theta\left(f^{-}S^{-}+2g^{-}\right). \qquad (46)$$

Replacing with (44)–(45), we obtain

$$(B-A-2S\kappa)\,S^{-}+2\,(A-\kappa+S\kappa)=\theta\left(\left(B-A-2S^{-}\kappa\right)S^{-}+2\left(A-\kappa+S^{-}\kappa\right)\right)$$

from which we get by rearranging terms

$$S-S^{-}=\frac{1}{2}\,(1-\theta)\,\frac{-2\,(A-\kappa)-S^{-}\,(B-A+2\kappa\,(1-S^{-}))}{\kappa\,(1-S^{-})}$$

where $(A-\kappa)>0$ from (8) and $B-A>0$, so that $S-S^{-}<0$.

As a consequence, as long as the pipeline capacity is fully used but the constraint is not binding for the downstream companies, and as long as the stored quantities remain non-negative, storage regularly decreases with time and quantities marketed shift from the high price to the low price season accordingly. It is straightforward to check using (44)–(45) that this implies an increase in the storage access price and a decrease in the pipeline access price.

This is the equilibrium solution as long as storage is used ($S\geq 0$) and as long as the binding capacity solution is not feasible, that is, as long as condition (22) is not satisfied.

If binding capacity is reached with positive storage, then demand in the downstream market is given by

$$\begin{aligned} S &= \frac{B-A-f^{b}}{2\kappa} \\ f^{b} &= \frac{(w_0+w_2)\,(B-A+a)-4\kappa w_2}{2\,(w_0+w_2)} \\ S &= \frac{B-A-a}{4\kappa}+\frac{w_2}{w_0+w_2} \end{aligned}$$

where, because of the binding capacity,

$$\frac{w_2}{w_0+w_2}=\frac{S^{-}}{2}.$$

In that case, the demand for storage over time satisfies

$$S=\frac{B-A-a}{4\kappa}+\frac{S^{-}}{2}$$

and moves toward the steady-state $\overline{S} = \frac{B-A-a}{2\kappa}$, which is positive if $B - A - a > 0$. Again, since pipeline is used at full capacity, changes in storage are reflected by shifts in quantities marketed from the high price season to the low price season, and access prices move accordingly, where, using (46),

$$\frac{g - \theta g^{-}}{f - \theta f^{-}} = -\frac{S^{-}}{2} < 0,$$

so that an increase in the storage price $f > f^{-} > \theta f^{-}$ translates into a decrease in the pipeline access price, $g < \theta g^{-} < g^{-}$.

Finally, notice that storage demand now depends exclusively on the storage access price, so that when storage stabilizes, its access price also does, reaching a steady-state value of $\overline{f} = B - A - 2\overline{S}\kappa = a$, equal to the unit cost of storage. When that happens, the pipeline access price is adjusted to satisfy the price cap constraint so that

$$\overline{f}S + 2g = \theta\left(\overline{f}S + 2g^{-}\right)$$

yielding a decrease in pipeline access price

$$g = g^{-}\theta - \frac{1}{4}a\left(1-\theta\right)\frac{B-A-a}{2\kappa}.$$

The decrease in storage quantities at the steady-state with respect to the situation without PCR is given by

$$S^{l} - \overline{S} = \begin{cases} \frac{A-r-\kappa}{2\kappa} & \text{if } B - A > a \\ \frac{B-\kappa-r-a}{2} & \text{otherwise} \end{cases}$$

where $A - r - \kappa \geq 0$ according to (8). Clearly, quantities transported increase with the imposition of a price cap, until full capacity is reached in the low price season, where the increase in total quantity transported is given by

$$1 - Q_1^{l} = \frac{3\kappa + r - A}{2\kappa}.$$

**Consumer surplus**

Consumer surplus is given by

$$CS = \frac{\left(Q_1 + \gamma\right)^2}{2} + \frac{\left(1 + S - \gamma\right)^2}{2},$$

where $\gamma$ is the reduction in storage from one year to the next, which translates into an increase in the quantity marketed in the first season, so that $(Q_1 + \gamma) + (1 + S - \gamma) = S + Q_1 + 1 = 2$ and $0 < \gamma < S$. Rearranging, we obtain

$$\begin{aligned} CS &= \gamma\left(-S + \gamma + Q_1 - 1\right) + \frac{1}{2}Q_1^2 + \frac{1}{2}\left(S+1\right)^2 \\ &= \gamma\left(-2S + \gamma\right) + \frac{1}{2}Q_1^2 + \frac{1}{2}\left(S+1\right)^2 \\ &< \frac{1}{2}Q_1^2 + \frac{1}{2}\left(S+1\right)^2, \end{aligned}$$

showing that any shift of the marketed quantities from the high price season to the low price season results in a loss in consumer surplus.

**Welfare**

During the period where capacity is not binding, access prices satisfy

$$\begin{aligned} f &= \left(B - A - 2S\kappa\right) \\ \Delta_f &= 2\kappa\gamma \\ g &= A - \kappa + S\kappa \\ \Delta_g &= \kappa\gamma \end{aligned}$$

where $\Delta_g$ is the decrease in the pipeline access fee, $\Delta_f$ is the increase in the storage access fee, and $\gamma$ is the reduction in storage quantities from one year to the next.

As a consequence, the impact of the PCR during that period on profits and welfare is, for the pipeline company:

$$\gamma\left(A - B + a - 2\kappa + 2\kappa\left(2S - \gamma\right)\right)$$

while for the downstream company it is given by:

$$2\gamma\left(-2S\left(\kappa - 1\right) + \kappa + \gamma\left(\kappa - 1\right)\right)$$

so that the impact on total welfare is:

$$\gamma\left(A - B + 2S + a - \gamma\right).$$

Notice that the impact of the regulation is always an increase in the profit of the downstream companies,

$$\begin{aligned} -2S\left(\kappa - 1\right) + \kappa + \gamma\left(\kappa - 1\right) &> -2\left(\kappa - 1\right) + \kappa - \gamma + \kappa\gamma \\ &> \frac{3}{2}\left(\gamma - 1\right) - \gamma + 2 \\ &= \frac{1}{2}\left(\gamma + 1\right) > 0, \end{aligned}$$

while the impact on pipeline profit and total welfare can be positive or negative (see for instance Figures 4 and 5).

In the long run, at the steady-state, the impact of the PCR is the following:

1. Profit of the pipeline company is given by $2(g - r)$ since either the access price is equal to $a$ or storage is no longer used, so that it is decreasing over time since $g$ is decreasing.
2. Profit of the downstream companies is given by $A + B + c_1 - c_2 - \overline{S}\left(A - B + 2\overline{S} + a\right) - 2 - 2g$ so that it is increasing over time since $g$ is decreasing
3. Consumer surplus is constant since prices and quantities no longer change
4. Total welfare is then constant over time. It is clear that the decrease in profit of the pipeline owner is completely captured by the downstream companies in the steady-state.

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