

Some Economics of Seasonal Gas Storage*

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Abstract

We propose a model of seasonal gas markets which is flexible enough to include supply and demand shocks while also considering natural gas as an exhaustible resource. We analyze theoretically the impact of policies (price caps, tariffs, cross subsidies) on prices and quantities consumed or stored. Using US data, we estimate the model's structural parameters and test economically founded restrictions. This evaluation is combined with the theory to give insights into past or envisaged public interventions.

1 Introduction

As energy markets become tenser and dependency on foreign imports increase in most economies, it is a challenging task to draw the overall picture of the modern gas industry. Our model is inspired by a number of features that characterize the US gas market. The USA was one of the first countries to make widespread use of natural gas and, as recently as the 1970s, accounted for more than half the world's consumption; it is still the largest consumer of natural gas in the world (about a quarter of the total) and also the largest importer (World Energy Review, 2004). Gas consumption being strongly influenced by weather and supply being relatively inflexible, storage primarily serves to avoid oversized extraction and transportation infrastructures and

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to limit excessive price fluctuations.¹ We aim at analyzing in a coherent framework this industry by focusing on the economics of seasonal storage, including long-run trends and the impact of public policies. By estimating and testing our model on US data, we argue that our approach is empirically well founded.

Regulatory reforms and the issue of security of supply have reactivated the interest in energy markets. The recent empirical literature on gas storage has devoted great care to developing specifications for the estimated equations. In Modjtahedi and Movassagh (2005), the aim is to test on high frequency data the basic theory of storage. Seasonal effects were ignored then filtered in a way that offers unclear guarantee on the economic consistency of the estimates; as the authors recognize in their conclusion, “the simple theory of storage seems to leave out some important variables affecting the natural gas futures market.” Pindyck (2002) provides a structural approach to various energy commodity markets. Consumption being assumed to be price inelastic, the approach is acceptable insofar as daily and weekly data are used to describe the trade-off between producing and reducing inventory, but it might not to capture significant phenomena linked to demand flexibility. Uría and Williams (2005) show the importance of the temporal aggregation in a model that accounts for injection and withdrawal decisions as a function of the price spreads on NYMEX and the stock level. The authors suggest that, especially with monthly data, regulatory requirements and seasonal effects limit the responsiveness of injection decisions in California to the futures market. However, in all these empirical papers, seasonal effects are more often evoked as an encumbrance than as an object of study. This explains our recourse to lower frequency data. The medium term that we analyze has particularities that deserve attention, despite the statistical limitations of the exercise (limited data, difficulty to filter finely trend or short term effects).

In the theoretical literature, the “supply of storage” models (Kaldor, 1939, Working, 1948, Brennan, 1958) are mainly interested in the role of storage when the economy experiences unexpected shocks. The analysis develops the notion of convenience yield, which explains the residual spread between future and actual prices once production, marketing and carrying costs have been accounted for. As Routledge et al. (2000) convincingly explain, the convenience yield must be seen as an embedded timing option, whose value is null for predictable variations like seasonal effects. These effects have been considered as a theoretical issue that can be treated in general purpose

¹For the advantage of storage as a means to absorb major supply shocks, see Chaton, Creti and Villeneuve (2005).

models (Brennan, 1960, Williams and Wright, 1991, Routledge et al., 2000). Very few papers tackle the specific issues of seasonal storage. Pyatt (1978) considers continuous time stationary demand and supply subject to a fixed seasonal pattern that might not correspond. He shows that storage regulates the rate at which output increases over time. For instance, if storage costs are determined entirely by interest charges, the results of Pyatt's analysis lead to the conclusion that when stocks are being held, the rate at which prices should grow is given by the rate of interest. Lowry et al. (1987) focus on the role that storage plays in allocating supplies within the year, analyzing markets for the US soybean market, when both demand and production are random. The key construct of the model is that the expected price function that links ex ante price expectations with carryout form the current period and in the last quarter of the year, with planted acreage. The authors characterize competitive speculative storage and in particular estimate the expected price function using computational rational expectations methods. This allows to discuss the behavior of quarterly variables in response to change in the storage carrying costs. Some effects that cannot be obtained from annual model are shown: in particular, decreasing the carrying charge causes the mean annual price and the mean prices in quarters 2,3, and 4 to decline, but the prices in quarter 1 rises, thus eliciting greater production and annual consumption. Interyear storage is also shown to increase the elasticity of demand, and thus stabilizing prices. This result provides a stochastic counterpart to Samuelson's (1966) theory of intraseasonal price movements under certainty.

While sharing the fundamental motivation with the papers on seasonal storage, inasmuch as we believe that marked seasonal patterns and considerable storage activity justify specific theoretical development, our approach distinguishes from theirs in several aspects. We focus on *excess supply* defined as stock variation between season and not on demand and supply separately. Modeling time as discrete and infinite, we characterize the competitive equilibrium and show under which conditions storage becomes seasonal (stocks are empty each year at the end of winter) in finite time and remains so. To closely match the fundamentals of the gas industry, we introduce capacity constraints, and we address the principal source of nonstationarity, namely the fact that natural gas is an exhaustible resource. Though our main focus is on deterministic shift of excess supply functions, we also develop a stochastic version of the model that proves useful in estimating simultaneously excess demand in the two seasons considered, corresponding to stock accumulation and depletion respectively, the arbitrage equation and the annual balance (zero stocks at the end of the year). Finally, we are more focussed on policy analysis than in price simulations and predictions.

Public interventions through storage have taken several forms. One set of models has analyzed the so-called “buffer stocks” that are used by public agencies to stabilize (mostly agricultural) prices (Vaugh, 1944, Oi, 1961, Massel, 1969). However, in these models storage costs and management are simply abstracted away. Some trade models (for example, Hueth and Schmitz, 1972, Just *et al.*, 1977, Devadoss, 1992) analyze public market interventions that protect national interests from imported price fluctuations. Welfare gains are computed by comparing the economic situation with and without stocks but storage is not optimized.

Williams and Wright (1991) have considerably enlarged the analysis of storage in dynamic stochastic models.² The solution involves careful algorithms and numerical simulations. The authors conclude that

“in all this discussion of the welfare effects of stabilization, the possible permutations of demand curvature, disturbance structure, initial conditions, supply elasticity and so forth seem nearly infinite. [...] That is the main point: few, if any, general proposition are possible. Often seemingly small differences in specifications or assumptions can reverse the sign of the presumed welfare effect.”

The same drawback arises when considering the effect of public government programs, and in particular, price cap policies. Unfortunately, the complexity of the underlying dynamic model makes the characterization of the effectiveness and efficiency of public interventions quite messy. Therefore, in the absence of clear-cut explanations, only “rough” quantitative estimates of various welfare effects of alternative government programs are computed numerically. As an alternative, basing our analysis on seasons, we clarify the impact of policies (price caps, tariffs, cross subsidies) on prices and quantities consumed or stored. We characterize the most efficient combination of instruments, for consumer countries that depend on foreign imports, to exercise monopsony power. This is an important methodological step since we show that many policies, employed in the past or proposed for the future, are just inefficient versions of the optimum.

A unique approach to some of the issues we address is to be found in Amundsen (1991), who investigates the social optimization problem of three operations: the extraction of natural gas from a reservoir up to its depletion, the supply to the storage unit (where either gas passes through or is stored), before it is transferred to end-users. The model, developed in continuous

²This impressive book encompasses and develops several works these authors have published on storage, as for example Wright and Williams (1982a, 1982b, 1984).

time, is rich and complex. The different predicted regimes (dynamics of extraction, inflows/outflows of storage, deliveries to end-users) are connected so intricately that policy analysis is practically impossible. To simplify the analytics in our model, years are split into two seasons. Stockpiling in summer and withdrawal in winter is shown to be consistent with random shocks and with exhaustibility of natural gas.

The overview of the US natural gas industry in Section 2 recalls basic facts on the yearly gas cycle and gives orders of magnitude. In Section 3, we expose the main assumptions. In Section 4, we characterize the competitive equilibrium under mild assumptions. The benchmark model opens the way to a detailed policy analysis in Section 5. Using US data, we estimate the model in Section 6 and we test a number of economic restrictions. The estimates enable us to evaluate the impact on storage, prices and welfare of the various policies evoked in Section 5. The final section concludes.

2 The US gas cycle

Weather is the primary driver of gas consumption. Because of winter heating, the seasonal pattern of gas deliveries is particularly striking in the residential and commercial sectors. Due to power-generation demand for summer cooling, the electric utilities' consumption is counter-cyclical (3.4 times higher in July and August than in January and February). Nevertheless, the overall seasonal pattern is not offset: the yearly cycle alternates between winter peaks and summer troughs. This is illustrated in Figure 1.

In contrast, extraction from gas wells as well as imports are practically flat (see Figure 2). A smooth production is motivated by cost-efficiency arguments driven by geological considerations.³ In addition, production and transportation are highly capitalistic and complementary; the economic optimum requires maximum utilization of the infrastructure and the profitability of the investment is typically secured by long term contracts with limited flexibility. Imports into the United States—almost entirely from Canada—show slightly more of a seasonal pattern than US production, largely because of the extensive use of Canadian upstream storage. The US gas industry is highly diversified with no single dominant company. According to the Natural gas Association, there are about 8,000 gas producers, ranging from small operations to major international oil companies. The five largest producers (BP, ExxonMobil, Chevron-Unocal, Devon Energy, ConocoPhillips, Chesapeake Energy) account for around 25% of total US output.

³For example, excess withdrawal of gas can submerge the wells with liquids (water, oil), causing interruption of the gas flow.

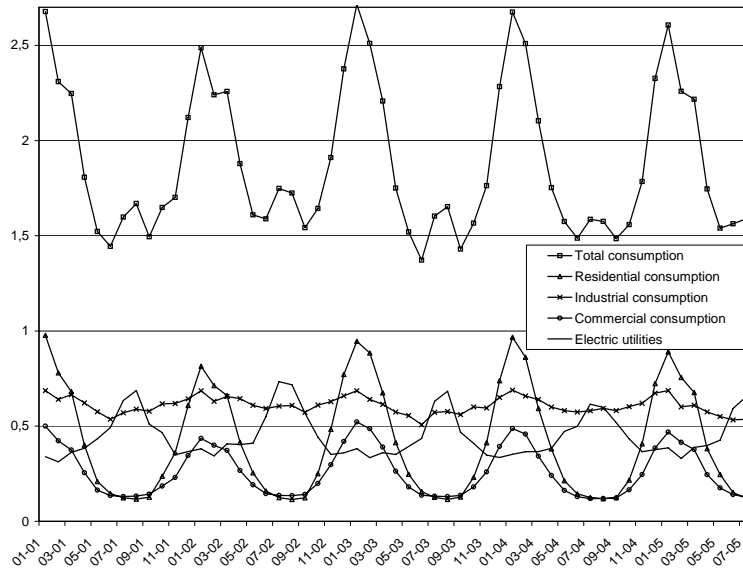


Figure 1: Gas consumption (total and by end use) (Tcf). Source: EIA.

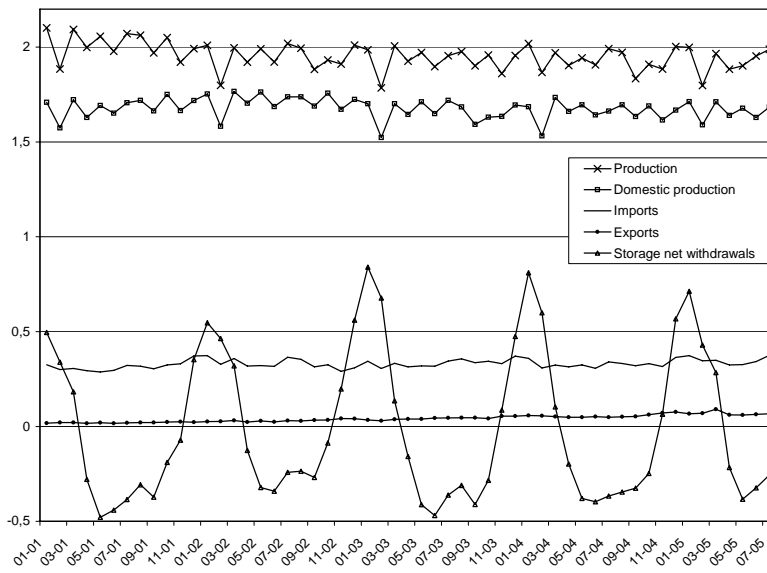


Figure 2: Withdrawals from gas wells and imports (Tcf). Source: EIA.

Storage plays a key role in balancing seasonal and short-term loads (compare total consumption in Figure 1 with net withdrawals in Figure 2). Natural gas, unlike many other commodities, requires specialized facilities. There are several types of storage: depleted gas or oil fields, aquifers, salt caverns, liquefied natural gas (LNG) tanks. Pipelines can also be used for balancing the transmission flows in order to keep gas pressure within design parameters. Each type has its own economic and physical characteristics. In general, storage facilities are classified according to flexibility (high or low withdrawal and injection rates). The two main classes are high deliverability sites (salt cavern reservoirs and LNG storages) and seasonal supply reservoirs (depleted fields and aquifers). Most existing gas storage in the United States is in depleted natural gas or oil fields that are close to consumption centers. Seasonal supply reservoirs are usually drawn down during the heating season (about 150 days from November to March) and filled during the non-heating season (about 210 days from April through October). High deliverability sites can be rapidly drawn down (in 20 days or less) and refilled (in 40 days or less) in order to respond to less expectable peak demands or system load balancing.

In 2005, the US industry had the capability to store approximately 8.2 trillion cubic feet (Tcf) of natural gas in about 391 storage sites around the country, mostly in depleted gas or oil fields. Working gas capacity makes up slightly less than 50% of the total. The rest goes to the base (or cushion) gas, i.e. the permanent volume of gas in a storage reservoir necessary to maintain adequate pressure and deliverability rates during the withdrawal season. In 2005, the gas withdrawn from storage to end use was 3.047 Tcf, which represents 13.2% of total gas supplies.

At the close of 2005, 394 underground natural gas storage facilities were operational in the US although 37 were marginal operations that reported little or no activity during the year. Between 1998 and 2005, 42 facilities were abandoned as uneconomic or defective, representing a loss of 223 billion cubic feet (Bcf) in total capacity, while 26 new sites, accounting for 212 Bcf of new capacity, were placed in operation. Yet, as abandoned capacity was always compensated for with new storage field development and the completion of several storage expansion projects, working gas capacity and design-day withdrawal capability (deliverability), the two prime measures of storage utility in today's natural gas storage market, grew steadily and substantially. By 2008, more than 73 underground natural gas storage projects are expected to be undertaken: they have the potential to add as much as 0.346 Tcf to existing working gas capacity (EIA, 2006). New storage sites are mainly salt caverns.

In recent years, the price of natural gas has followed an upward slope to reach unprecedented levels. The development of new production capacity is

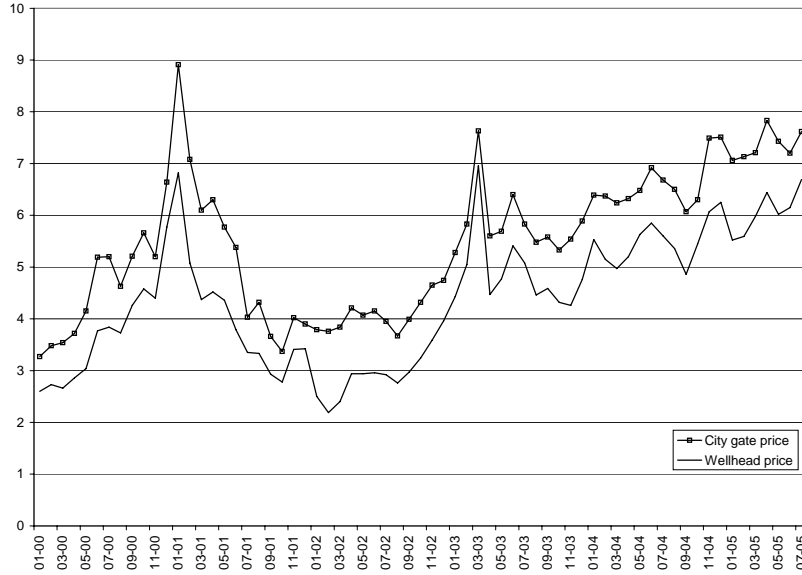


Figure 3: Monthly natural gas price (\$/Mcf). Source: EIA.

lagging behind growth in demand, which is also exacerbated by the use of gas for electric power production. Because of the existence of a significant amount of short-term fuel-switching capability in industry and power generation, interfuel competition plays a major role in day-to-day price setting. This demand-side flexibility limits the seasonal volatility of spot prices: in the Northeast and Mid-Atlantic, prices are effectively capped by prevailing heavy-fuel-oil price levels in the winter, when oil typically replaces gas in power generation and in some industrial uses. The ability of power generators to burn coal in the South effectively sets a ceiling price for gas in the summer. The sustained tension on the market results in large spikes when the temperature reaches unusually low levels in winter or unusually high levels in summer. Accidents like the breakdown in 2001 of the El Paso pipeline connecting California to Mexico or natural disasters like Hurricane Katrina in 2005 had similar effects. In 2006, the prices have returned to levels closer to historical average.

In this context, in contrast to previous decades, the seasonality of the price is hardly visible in Figure 3. However, over the last twenty years, the average price over the winter is significantly higher than the average price during the previous summer.

3 The model

Supply and demand. Time is discrete and infinite. A year is composed of two six-month periods; it starts with summer S and ends with winter W . A period is denoted by $y\sigma$ for year and season. The year after y is denoted $y + 1$, whereas the season that follows $y\sigma$ is $n(y\sigma)$ where n is for next, e.g. $n(yS) = yW$ and $n(yW) = (y+1)S$; $n^m(y\sigma)$ and $n^{-m}(y\sigma)$, with m a positive integer, indicate the m th period forward and backward respectively.

The strictly decreasing consumption function at period $y\sigma$ is denoted by $\text{Cons}_{y\sigma}[\cdot]$. The dependency on the current price only is grossly acceptable for relatively long periods, between which intertemporal substitution is limited. Domestic and foreign production (imports) at period $y\sigma$ is denoted by $\text{Prod}_{y\sigma}[\cdot]$. Production is non-decreasing with respect to the price. We assume that, for all $y\sigma$, $\text{Cons}_{y\sigma}[\cdot]$ and $\text{Prod}_{y\sigma}[\cdot]$ cross only once for some $p_{y\sigma}^0 > 0$. To characterize the difference between summer and winter, we only need the following inequalities: $p_{yW}^0 \geq p_{yS}^0$ and $p_{yW}^0 \geq p_{(y+1)S}^0$, $\forall y$. These weak restrictions stress the importance of seasonal effects (higher prices in winter) without assuming that the yearly cycle is repeated over time.

Competitive storage. The price in period $y\sigma$ is denoted $p_{y\sigma}$. Storage is assumed to be a competitive activity with constant returns to scale up to the maximum capacity K . If the capacity constraint is slack, the unit storage charge $\kappa_{y\sigma}$ is driven to the marginal cost c ; in general, $\kappa_{y\sigma} \geq c$. The interest rate from one period to the next is r .

The stock $G_{y\sigma}$, counted at the end of $y\sigma$, cannot be negative. It remains null if there is no expected benefit from storage, i.e. if

$$\frac{p_{n(y\sigma)}}{1+r} < p_{y\sigma} + \kappa_{y\sigma}. \quad (1)$$

The inequality means that the current price plus storage charge exceeds expected discounted selling price. In equilibrium, with positive storage, the no-arbitrage condition is

$$G_{y\sigma} > 0 \Rightarrow \frac{p_{n(y\sigma)}}{1+r} = p_{y\sigma} + \kappa_{y\sigma}. \quad (2)$$

Define the excess supply function

$$\Delta_{y\sigma}[\cdot] = \text{Prod}_{y\sigma}[\cdot] - \text{Cons}_{y\sigma}[\cdot]. \quad (3)$$

For each period, conservation of matter imposes the following dynamic equation

$$\Delta_{y\sigma}[p_{y\sigma}] = G_{y\sigma} - G_{n^{-1}(y\sigma)}. \quad (4)$$

Transversality condition. With endogenous prices and storage, the equilibrium could be a bubble in which the sequence of prices grows unboundedly after a certain period $y\sigma$

$$p_{n^{i+1}(y\sigma)} = (1+r) \cdot (p_{n^i(y\sigma)} + \kappa_{y\sigma}), \forall i. \quad (5)$$

Along this path, consumption shrinks and production grows period after period, implying ever increasing stocks, which is not credible. To avoid this anomaly, it suffices to impose a transversality condition ensuring that (5) is impossible, for example $\lim_{i \rightarrow +\infty} \frac{p_{n^i(y\sigma)}}{(1+r)^i} = 0$. Consequently, in any equilibrium with reasonably stable fundamentals, stocks have to revert from time to time to zero.

Equilibrium. In the absence of storage, periods are independent of each other. The equilibrium is the unique sequence of prices $p_{y\sigma}^0$ equalizing consumption and production ($\Delta_{y\sigma}[p_{y\sigma}^0] = 0, \forall y, \sigma$). If in some period $y\sigma$, prices are such that

$$\frac{p_{n(y\sigma)}^0}{1+r} > p_{y\sigma}^0 + \kappa_{y\sigma}, \quad (6)$$

then storage creates value. Consequently, if the price differential between successive prices is sufficiently large, the interest rate sufficiently low and storage costs sufficiently small, then there are stocks at the equilibrium.

Definition 1 (Competitive Equilibrium) *A competitive equilibrium starts in period $0S$, with some stocks G_{0S} ; it comprises a sequence of prices $p_{y\sigma}, \kappa_{y\sigma}$ with a storage policy $G_{y\sigma} \geq 0$ such that, for all $y\sigma$ after $0S$*

$$\left\{ \begin{array}{l} \text{if } \frac{p_{n(y\sigma)}}{1+r} < p_{y\sigma} + c \text{ then } G_{y\sigma} = 0; \\ \text{if } \frac{p_{n(y\sigma)}}{1+r} = p_{y\sigma} + c \text{ then } 0 \leq G_{y\sigma} < K; \\ \text{if } \frac{p_{n(y\sigma)}}{1+r} = p_{y\sigma} + \kappa_{y\sigma} \text{ with } \kappa_{y\sigma} > c \text{ then } G_{y\sigma} = K; \\ \Delta_{y\sigma}[p_{y\sigma}] = G_{y\sigma} - G_{n^{-1}(y\sigma)}; \\ \lim_{i \rightarrow +\infty} \frac{p_{n^i(y\sigma)}}{(1+r)^i} = 0. \end{array} \right. \quad (7)$$

Price-taking behavior of the agents, strictly increasing excess supply functions, linearity of the storage technology, all these hypotheses suffice to ensure that the competitive equilibrium maximizes the total surplus, obtained by adding consumers' and producers' surpluses each period discounted at the interest rate. We retrieve the classical virtue of competition.

4 Competitive storage

This section shows that the alternation between stockpiling in summer and complete utilization of the stock in winter is a robust feature of the model. This seasonality implies that price cycles are independent in a stochastic version of the model, with moderate shocks (Subsection 4.2) and in the long-run, with realistic trends (Subsection 4.3).

4.1 Transition and limit cycles

The current price being p , $N[p] \equiv (1+r)(p+c)$ denotes the price attained after one season of unconstrained positive stockholding. Consistently, $N^m[p]$ denotes the price attained after m seasons of *uninterrupted* stockholding.

Definition 2 *The economy is said to be regular if for all seasons σ , all years y and all prices p*

$$\Delta_{(y+1)\sigma}[N^2[p]] \geq \Delta_{y\sigma}[p]. \quad (8)$$

This condition restricts the rate at which supply and demand change over time. It is comfortably satisfied by purely cyclical economies, since then $\Delta_{(y+1)\sigma}[\cdot] = \Delta_{y\sigma}[\cdot]$ (an increasing function of the price) while clearly $N^m[p] > p$ for all m . The following proposition states that storage in regular economies is dominated by seasonal factors rather than by trends.

Proposition 1 (Convergence to seasonal pattern) *If the economy is regular, then in any competitive equilibrium, storage becomes seasonal (stocks are empty each year at the end of winter) in finite time and remains so.*

Proof. See Appendix A.1. ■

If the economy starts with huge reserves (e.g. domestic gas fields), the economy will experience a drainage phase of several years and will then follow the cyclical dynamics. Prices start low and increase steadily season after season, following the no-arbitrage equation. Once the stocks are exhausted, the seasonal dynamics consists of stockpiling in summer and depleting reservoirs in winter.

As years are independent of each other, we can now characterize their typical patterns. Assume a large K to ensure that $\kappa_{yS} = c$. If $p_{yW}^0/(1+r) > p_{yS}^0 + c$, the unique solution (p_{yS}, p_{yW}) is derived from conservation of matter (equation 4) and the no-arbitrage condition (equation 2). As predictable, storage smoothes prices and quantities: the summer price increases and winter price decreases, while the opposite holds for consumption. The winter price remains higher than the summer price.

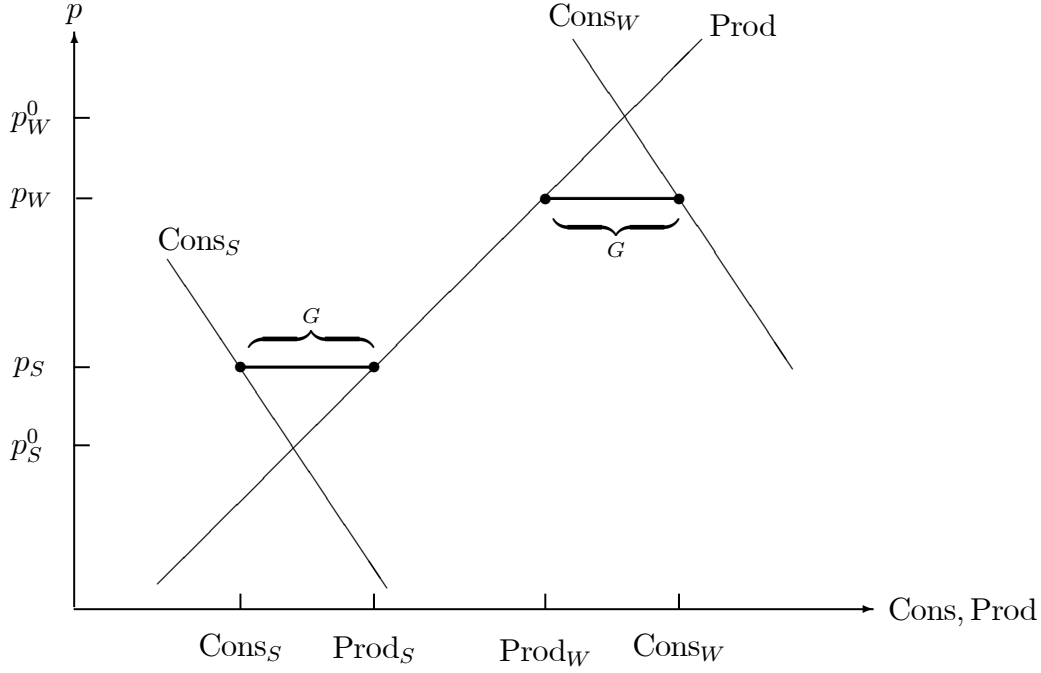


Figure 4: Unconstrained Competitive Storage.

Figure 4 illustrates the case of the two-season equilibrium with linear demand and a production function independent of the season (the year index is dropped). If $p_W^0/(1+r) < p_S^0 + c$, then no stocks are accumulated ($p_W = p_W^0$ and $p_S = p_S^0$). If the storage capacity K is saturated at the end of the summer, we have one more unknown (κ_S), and one more equation ($G = K$). The endogenous storage charge generates a scarcity rent $\kappa_S - c$.

4.2 Shocks

The property that stocks are fully used at the end of the winter is generalizable to a stochastic version of the model. Assume that season specific shocks impact the excess supply function (i.e. supply and demand) and that this shock is known only at the beginning of the season. This means simply that decisions made one season before were not informed of the magnitude of the current shock, whereas decisions taken during the season take it into account. Temperature or weather conditions in general are good examples.

We only consider stationary equilibria to eliminate bubbles as well as transitory phases in which reserves are depleted before the economy relies on domestic production and imports. The idea is that if the shocks are limited

(support is bounded), then there is no possible state of the economy in which speculators store at the end of the winter for the coming summer.

The first step is to solve the equilibrium in which the year starts and finishes with empty stocks. The resulting equilibrium prices are random: the summer price depends on the summer shock, the winter price depends on the summer and winter shocks. The second step is to search for conditions under which storage from winter to summer is never desirable in any realization of the possible states of nature. It suffices to compare the smallest possible winter price with the expected summer price. If the former is high enough (or equivalently, if the latter is low enough), then there is no arbitrage and storage is never desirable. This implies that stockout at the end of winters is systematic. The condition to obtain this result is to have shocks of limited magnitude (with respect to the no-storage price range) in both summer and winter.

4.3 Cycles and trends with exhaustible supply

In what precedes the present section, we considered equilibria supported by regular fundamentals. We address here the principal source of nonstationarity, namely the fact that natural gas is an exhaustible resource. Production is determined by intertemporal arbitrage as exposed in Hotelling (1931) and by the transportation capacity from gas fields to the consumers. The equilibrium is never stationary (except if production and consumption become null) and the economy crosses three significantly different phases that we characterize.

4.3.1 A simple model

Gas reserves are finite and we assume that they are concentrated at a unique wellhead Wh . Consumption is concentrated in a unique region B (Burnertips). A pipeline of capacity Q (per period) connects Wh and B . Marginal extraction cost is c_{Wh} , while marginal transportation cost along the pipeline is c_{Tr} (both c_{Wh} and c_{Tr} are assumed to be constant and stationary).⁴ Storages are located at B . Each period, gas can either be kept in the original field (i.e. not produced) or stored in the consumption region once it has been transported there. The difference between the gas field and storages lies in stockholding costs (zero in the former and c per unit per period in the latter). See Figure 5.

⁴Remark that Q could alternatively be interpreted as the maximum capacity of the production sector.

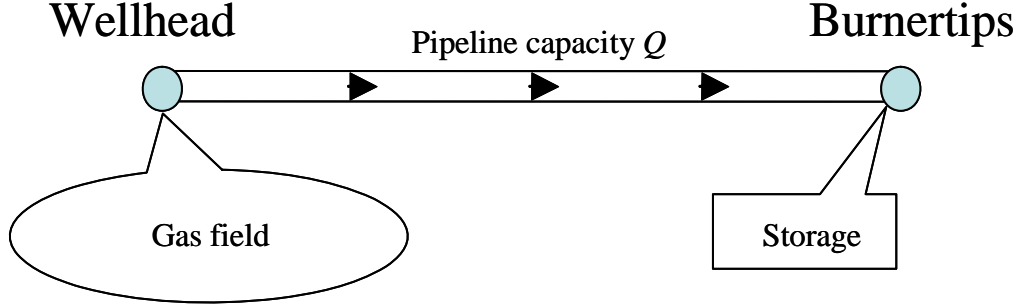


Figure 5: Extraction, storage, burning.

We assume price-taking behavior at all nodes and also that all arbitrage possibilities (through transportation or storage) are exploited. The price at node i ($= \text{Wh}, B$) and period $y\sigma$ is denoted by $p_{y\sigma}^i$. The marginal profit at Wh for period $y\sigma$ is $p_{y\sigma}^{\text{Wh}} - c_{\text{Wh}}$, which, according to the Hotelling rule, grows at rate r . This implies

$$\frac{p_{n(y\sigma)}^{\text{Wh}}}{1+r} - p_{y\sigma}^{\text{Wh}} = -\frac{r}{1+r} c_{\text{Wh}} < 0. \quad (9)$$

The wellhead price grows more slowly than the interest rate.

To simplify matters, we assume that, during the first period, stocks are empty (no domestic gas fields). We consider an economy in which gas demand functions in winter and summer are stationary. Inverse demand functions in summer S and winter W are denoted by $p_S[\cdot]$ and $p_W[\cdot]$ respectively. To keep the economically appealing case in which seasonal storage is desirable when imports are maximum (line is congested), we assume that $p_W[Q]/(1+r) > p_S[Q] + c$. We describe the situation at “the beginning” (low prices), during the transition (intermediate prices) and at “the end” (high prices). A more realistic description would be a model in which fields are increasingly costly or increasingly remote from the consumption region as depletion goes on. The effects for consumers would remain roughly identical with similar phases.

4.3.2 The three phases of exhaustion

Low prices. Demand is high and the pipeline is fully used in both seasons. In the absence of storage, prices would be $p_{yS}^B = p_S[Q]$ and $p_{yW}^B = p_W[Q]$. The assumption above on these prices ensures that there is some storage \tilde{G}

taking place, the unique solution to the following no-arbitrage equation

$$p_W[Q + G]/(1 + r) = p_S[Q - G] + c. \quad (10)$$

The equilibrium prices are $p_{yS}^B = p_S[Q - \tilde{G}]$ and $p_{yW}^B = p_W[Q + \tilde{G}]$.

The economy follows a trend at Wh, but is strictly cyclical at B (seasonal consumer prices and quantities consumed or stored are constant). The *total profits* (mineral rent plus pipeline congestion rent) are $(p_S[Q - \tilde{G}] - c_{Wh} - c_{Tr})Q$ in summer and $(p_W[Q + \tilde{G}] - c_{Wh} - c_{Tr})Q$ in winter. (Storage is competitive and thus produces no net profit.) Remark also that this globally constant rent is gradually transferred from the pipeline owners to the reserve owners; indeed, $p_{y\sigma}^B$ increases over the years, whereas $p_{y\sigma}^{Wh}$ is stable. Over time, the transportation network becomes less and less profitable.

Intermediate prices. The line is congested in one season only.

If the pipeline is fully used in winter only, the assumption according to which $p_W[Q]/(1 + r) + c > p_S[Q]$ ensures that some storage will take place. The price in summer is the wellhead price plus transportation charge c_{Tr} and the price in winter is driven by the no-arbitrage condition

$$p_{yS}^B = p_{yS}^{Wh} + c_{Tr}, \quad (11)$$

$$p_{yW}^B = (1 + r)(p_{yS}^B + c). \quad (12)$$

This is the normal, realistic, case.

In the case where congestion occurs in summer only,

$$p_{yS}^B > p_{yS}^{Wh} + c_{Tr}, \quad (13)$$

$$p_{yW}^B = p_{yW}^{Wh} + c_{Tr}. \quad (14)$$

By rearranging these two equations, we find

$$\frac{p_{yW}^B}{1 + r} - p_{yS}^B < -\frac{r}{1 + r}(c_{Wh} + c_{Tr}). \quad (15)$$

This precludes storage (the RHS is obviously smaller than c). Congestion in summer always goes with no storage; this case is therefore quite unrealistic but it cannot be logically excluded without making further assumptions on demand functions.

High prices. The line becomes uncongested in both periods and necessarily $p_{y\sigma}^B = p_{y\sigma}^{Wh} + c_{Tr}$ for each period, i.e.

$$\frac{p_{n(y\sigma)}^B}{1 + r} - p_{y\sigma}^B = -\frac{r}{1 + r}(c_{Wh} + c_{Tr}) < 0 < c. \quad (16)$$

Prices grow more slowly at B than at Wh , a fortiori more slowly than the interest rate. This eliminates any incentive for storage and the consumers rely entirely on current imports. Remark that the mineral rent remains now integrally in the hands of the producers.

The first phase is specially relevant for economies that depend highly on energy imports. Price observed at the local level may well be stationary for a while, *even if* the world price follows the Hotelling rule. An interesting feature of the second phase is diminishing reliance on storage and dissipation of the pipeline rent. Predictions as to the date at which the last phase arrives are fragile as they are highly dependent on demand characteristics (elasticity and growth) and investment in transport infrastructures (Q cannot be considered as an exogenous constant in the long run).

5 Policy analysis

5.1 Background

Deregulation of the US gas industry was initiated by the 1978 Natural Gas Policy Act, which partially decontrolled wellhead prices and relaxed some restrictions on interstate pipeline transportation. This move, prompted by gas shortages in the 1970s which were blamed on wellhead price controls, coincided with rising demand. In these conditions, producers were able to bid up wellhead prices in the deregulated market and impose onerous long-term take-or-pay commitments on the pipeline companies. A slump in gas demand in the early 1980s resulting from the recession and higher prices led to the emergence of surplus supply, known as the gas bubble, and downward pressure on prices. The FERC Order 436, issued in 1985 and implemented in 1986, was intended to help resolve the pipeline companies' financial difficulties. It encouraged the opening of access to the US gas pipeline system on a voluntary basis and increased competition in domestic markets. Finally, the Wellhead Decontrol Act of 1989 specified the phased removal of all remaining controls on wellhead gas prices by the end of 1992.

The liberalization of the gas sector encompasses today deregulation of the retail market. In 2003, in the US, some 22 states launched either residential pilot programs (EIA, 2003) or broader customer choice programs, leaving end-use clients free to obtain least-cost service by contracting separately with gas sellers and transportation companies. It must be noted that the delivered price to small-volume customers exhibits small or delayed fluctuation, because the natural gas commodity price is a small percentage of the delivered

price.⁵ Nevertheless, providing unbundled services to residential customers poses a host of questions for regulators, which include in particular, the need to redefine public service obligations, such as tariff uniformity and an eventual price cap for small-volume consumers. According to the FERC Energy Policy Act of 2005, moderating the recurrence and severity of “boom and bust” cycles while meeting increasing demand at reasonable prices is one of the major challenges facing the US natural gas industry today. At the core of the policy are proposals to ensure adequate domestic energy supply and infrastructure.

Although nowadays there would seem to be limited scope for government intervention in the gas sector, public decisions are rarely motivated by pure efficiency considerations, especially when consumers and producers are geographically separated, or more generally when they have different political weights.⁶ Some States, like Ohio, impose public utility excise tax (levied on natural gas utilities, but also pipeline companies, heating companies, waterworks, and water transportation companies that do business). Other States, like North Carolina, impose an excise tax on piped natural gas received for final consumption. In emergency situations, gas price ceilings could be imposed, even though in practice these measures can be temporary or not implemented. This was the case, for instance, in California, in 2001, when the Long Beach City Energy Director, considering that residential gas bills would likely have increased by about 34% compared to the previous year, proposed a ceiling of \$1 a therm; this measure was not accepted by the California State Lands Commission. In Argentina, a price ceiling on natural gas prices was set in 2002 after the country’s economic collapse, but this led to a surge in natural gas usage, exceeding the country’s gas supply. To prevent a similar crisis in the future, the Argentine government has promised to raise, and eventually liberalize, natural gas prices, though there is no firm timetable in place for this liberalization. The decision of the Aloha State to put into effect in August 2005 a new state law slapping a ceiling on gasoline prices pegged to average prices on the mainland, has raised a new debate on the surplus enhancing effect of price controls in the oil and gas industries (see Committee on Energy and Commerce, 2005).

⁵Following EIA estimates (EIA, 2001), for residential users, the gas commodity price is only about 30 percent of the delivered price, and the remainder reflects the cost of services between the wellhead and the burnertip on a firm service basis. Moreover, effective price signals to residential customers also are limited by residential billing and metering procedures, such as levelized billings.

⁶In a context where risk is a driving motive for storage, public intervention can also consist of “antispeculation” measures. For a detailed analysis of this issue, see Chaton, Creti and Villeneuve (2005).

This section analyzes in detail price caps as a basic example of what can be expected from policy; we pursue by showing that price caps (as well as other simple policies) exhibit limitations that can be transcended; for this purpose, we characterize the best outcome a government can implement to maximize consumers' surplus. We conclude with important clarifications on implementation in a competitive context (role of tariffs, taxes and subsidies, and contracts).

5.2 Price cap

The regularity assumption blocks the propagation of regulation applied in one year to other years (see Proposition 1). Consequently, the year index y will be dropped in the following to make for easier reading.

A price cap only forces prices not to exceed a certain value (say \bar{p}). Markets are otherwise competitive (price taking behavior), but in case of disequilibrium between supply and demand during peak season, consumption is rationed. If \bar{p} is higher than the winter price expected in the absence of a ceiling, then it has no effect on the economy. If it is too low, it completely discourages storage since the price dynamics motivating stockpiling in summer is sterilized; this happens if $\bar{p} < (1+r) \cdot (p_S^0 + c)$.

Proposition 2 *With a non-extreme price ceiling $((1+r) \cdot (p_S^0 + c) < \bar{p} < p_W)$,*

1. *Storage \bar{G} , seasonal prices $\bar{p}_W = \bar{p}$ and $\bar{p}_S = \frac{\bar{p}}{1+r} - c$ decrease as \bar{p} decreases; consumers are rationed in winter;*
2. *A price cap slightly below the unconstrained competitive winter price increases consumers' surplus.*

Proof. See Appendix A.2. ■

Though price ceilings succeed in reducing prices, price variability remains little affected and storage is discouraged. The latter effect was mentioned in, e.g., MacAvoy and Pindyck (1973) and Wright and Williams (1982b).⁷

If the government in charge of setting the price cap defends the consumers' interest only, then a price cap is desirable. There are obvious limits to these gains: approximately, welfare loss due to rationing increases quadratically with respect to the difference between the price cap and the free price, whereas benefits remain roughly linear. Rationing was common in the United

⁷Symmetrically to the discouragement effect of the price cap, a policy that forces the market price to be *higher* than the competitive one will create excess storage and therefore will sacrifice economic efficiency (Helmberger and Weaver, 1977). Producers gain from the government policy, while consumers lose.

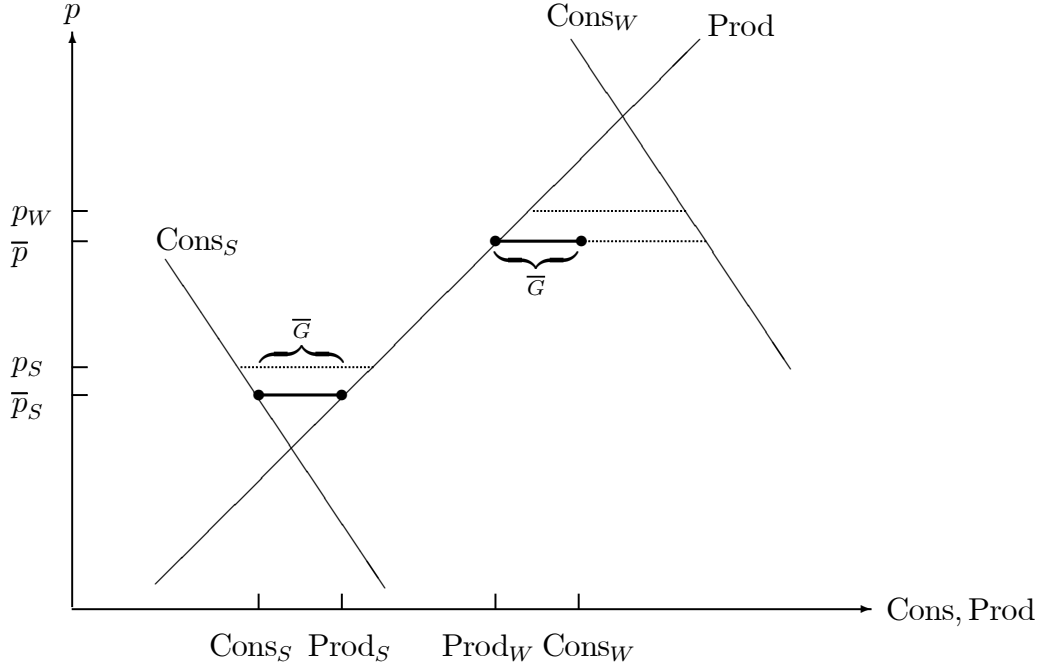


Figure 6: Competitive Storage with Price Ceiling

States during the 1970s' winters, as a consequence of restrictive regulatory policy on wellhead prices.⁸

As price caps are a way of exerting market power, the result is in line with monopsony pricing theory (here the state “coordinates” consumers through the ceiling), with intertemporal effects due to competitive storage. The practical difficulty is not to go too far once the cycle is fully taken into account. An improvement is to combine the price cap and the inevitable winter rationing with some *summer* rationing. As the rationing cost is approximately quadratic with respect to the difference between demand and supply, rebalancing rationing between seasons enhances welfare. Ultimately, augmenting the price cap with complex side measures appears to be a daunting task. Taxes are the most effective means of implementing generalized rationing, as the following shows.

5.3 Optimal allocation

To optimize the consumers' or the domestic surplus, we need to be more specific as to fundamentals. The simplest approach is to represent consumers

⁸Notice that in our model those who produce and those who store are both subject to the price cap. Clearly, other formulations are possible. If the local distribution companies can store, their storage might not be subject to the cap while production is.

with an intertemporal utility function; the arguments are gas consumption and a separable *numéraire* that could be seen as labor. The consumers surplus can then be written

$$U_S[q_S^C] - m_S + \frac{U_W[q_W^C] - m_W}{1+r}, \quad (17)$$

where U_S and U_W are increasing and concave utility functions, q_σ^C is season σ gas consumption and m_σ is season σ expenditure. The year index y is dropped without loss of generality. Domestic production is simply modelled through cost functions $C_S^D[\cdot]$ and $C_W^D[\cdot]$; imports are represented with the inverse supply functions $p_S^I[\cdot]$ and $p_W^I[\cdot]$ respectively. Storage is assumed to be domestic.

The optimal policy in the interest of the residents (consumers plus domestic producers) can be characterized using the following method: all quantities (q_S^C and q_W^C , domestic productions q_S^D and q_W^D , and imports q_S^I and q_W^I) are taken as choice variables. The government solves

$$\left\{ \begin{array}{l} \max_{q_S^C, q_W^C, q_S^D, q_W^D, q_S^I, q_W^I} U_S[q_S^C] - C_S[q_S^D] - p_S^I[q_S^I]q_S^I \\ \quad + \frac{U_W[q_W^C]}{1+r} - \frac{C_W[q_W^D]}{1+r} - \frac{p_W^I[q_W^I]q_W^I}{1+r} \\ \quad - c(q_S^D + q_S^I - q_S^C) \\ \text{such that } q_S^D + q_S^I + q_W^D + q_W^I \geq q_S^C + q_W^C, \\ \quad q_S^D + q_S^I \geq q_S^C. \end{array} \right. \quad (18)$$

We only discuss the case of positive storage at the end of the summer (the last constraint is slack). The necessary and sufficient conditions, after elimination of the Lagrange multipliers, are

$$U'_S[q_S^C] = C'_S[q_S^D], \quad (19)$$

$$U'_W[q_W^C] = C'_W[q_W^D], \quad (20)$$

$$U'_S[q_S^C] + c = \frac{U'_W[q_W^C]}{1+r}, \quad (21)$$

$$U'_S[q_S^C] = p_S^I[q_S^I] + p_S^{II}[q_S^I] \cdot q_S^I, \quad (22)$$

$$U'_W[q_W^C] = p_W^I[q_W^I] + p_W^{II}[q_W^I] \cdot q_W^I, \quad (23)$$

$$q_S^D + q_S^I + q_W^D + q_W^I = q_S^C + q_W^C. \quad (24)$$

The interpretation is straightforward: the consumers' marginal utilities should equal domestic marginal costs; consumers' intertemporal MRS should satisfy the no-arbitrage equation (domestic storage must not be distorted); each period, the government exerts monopsony power on foreign producers.

Proposition 3 *Compared to the competitive allocation, consumption, domestic production and imports at each period decrease. There are economies in which storage is smaller and others in which it is greater.*

Proof. See Appendix A.3. ■

Storage may be greater with the optimal policy than under *laissez-faire*. This possibility was inexistent with the less efficient price cap policy. Assume for example that winter demand is very inelastic compared to summer demand. Since production is reduced in both periods, winter demand can be met only by discouraging summer demand. Given our assumptions on elasticities, this is the less distortionary choice; accordingly, one has to increase the stored quantity of gas.

5.4 Implementation

The allocation maximizing domestic surplus can be sustained with tariffs on imports each season (denoted by τ_S and τ_W). These tariffs are just the wedge between domestic and import prices. For instance natural gas imported from Algeria and other sources must still pay a small merchandise processing fee to the US customs services. No intervention is required in the domestic market (storage sector included): consumption is not rationed and domestic storers simply arbitrage. The domestic prices are simply denoted p_S and p_W .

$$\begin{aligned} \text{Domestic prices: } & p_S = U'_S[q_S^C] = C'_S[q_S^D], \\ & p_W = U'_W[q_W^C] = C'_W[q_W^D]. \\ \text{Import prices: } & p_S^I = p'_S[q_S^I], \\ & p_W^I = p'_W[q_W^I]. \\ \text{Tariffs: } & \tau_S = p'_S[q_S^I]q_S^I > 0, \\ & \tau_W = p'_W[q_W^I]q_W^I > 0. \end{aligned}$$

The interpretation of price policy in terms of taxation unifies the view on the various policies that have been or could be observed or proposed. Price caps are more efficiently implemented with tariffs/tax than with rationing: efficient rationing is extremely demanding in terms of information because it requires knowledge of the private marginal valuations of all the consumers whereas the tariff merely requires uniform application. In this sense, we agree with Wright and Williams (1982b) in that “a price ceiling can crudely substitute for an optimal tariff, if this latter cannot be implemented.”⁹

⁹Wright and Williams (1982b) assumed that consumption is rationed by marketable coupons distributed to consumers. Therefore, a kind of “secondary spot markets” must exist for rationing to be efficient (the least costly in terms of welfare). This idea goes against the principle of a price cap, since some transactions are indeed made above the

Above all, optimal tariffs implement an optimally balanced “rationing” (or preferably demand containment) between summer and winter, whereas the version we discussed in 5.2 concentrates the effort on winter, which is suboptimal. Moreover, as it is typical of second best policy, this primary distortion must be mitigated by other distortions. The government may wish to compensate the undesirable effects of the basic price cap (discouraging storage) with subsidies on storage (or, if one prefers, subsidies across periods). Nevertheless, tariffs rather than cross subsidies are more efficient.

More subtle than rationing, interruptible contracts allow pipelines and local distribution companies to curtail capacity during winter periods. The theory of interruptible contracts was initiated by Wilson (1989), who studied priority pricing in electricity markets subject to supply shocks. This pricing system involves serving customers in a given order until capacity is met; any shock can be treated with this rule. The order is pre-determined by the self-selection of customers into classes that are differentiated by their service priority and the price. This determines those consumers who can be interrupted at the least cost, thus economizing production capacity.

The analogy with our seasonal economy is as follows. If we consider that customers’ willingness to pay are ranked identically regardless of the season (instead of the state of nature), Wilson’s theory can be adapted to account for gas annual contracts (i.e. bundles of summer and winter gas) as convenient substitutes for explicit rationing or tariffs. In our model, this would result in three classes of consumers: those paying large bills to get gas in summer and in winter, those paying less to be served one season (presumably winter for heating), and finally those who do not consume at all. These arrangements, often suspected of hiding cross subsidies, might also have played the role of season adjusted prices.

6 Applications

The liberalization of the US gas market started nearly twenty years ago. The experience is now sufficiently well established to provide data on prices and quantities that can be used to estimate structural parameters and test a number of our model’s predictions (Subsection 6.1). Though the results are satisfactory in many ways, the accuracy of the estimates drawn from the aggregate approach is insufficient to formulate firm predictions. With this reservation in mind, we propose a comparative simulation of the impact (Subsection 6.2) of various price policies discussed in Section 5.

ceiling. In all events, such markets seem to be quite unlikely to emerge at the final consumption level.

6.1 Estimation of the model

The econometric specification is based on the stochastic model discussed in Section 4.2. The empirical counterpart of the model requires the arguably exogenous controls $\mathbf{Z}_{yS} = (T_{yS} \ Y_{yS})'$ and $\mathbf{Z}_{yW} = (T_{yW} \ Y_{yW})'$ (season average temperature and GDP).¹⁰

The observed variables for season $y\sigma$ are therefore

$\Delta_{y\sigma}$: variation of the stock;

$p_{y\sigma}$: average gas price;

$Y_{y\sigma}$: GDP;

$T_{y\sigma}$: average temperature.

For each year, the equilibrium involves four equations: excess supplies in summer and in winter, price arbitrage and annual balance. We use the following linear specification

$$\Delta_{yS} = \beta_1^0 + \beta_{1p}p_{yS} + (\beta_{1T} \ \beta_{1Y})\mathbf{Z}_{yS} + \varepsilon_{y1} \quad (25)$$

$$\Delta_{yW} = \beta_2^0 + \beta_{2p}p_{yW} + (\beta_{2T} \ \beta_{2Y})\mathbf{Z}_{yW} + \varepsilon_{y2} \quad (26)$$

$$Ep_{yW} = \beta_3^0 + \beta_{3p}p_{yS} \quad (27)$$

$$\Delta_{yW} = \beta_4^0 + \beta_{4\Delta}\Delta_{yS} + \varepsilon_{y4} \quad (28)$$

All shocks have distributions with zero mean. Shocks ε_{y1} and ε_{y2} are unexpected random shifts in the *excess supply* functions (thus they can originate in demand or supply) that are observable by economic agents when they make their production or consumption decisions; as for ε_{y4} , see Tests 1 and 2 below.

We test the following restrictions:

1. $\beta_4^0 = 0$ and $\beta_{4\Delta} = -1$: total annual excess supply is null on average.
2. $\Delta_{yS} + \Delta_{yW}$ is not correlated with $\Delta_{(y+1)S}$: no catch-up, weak interannual effects.
3. $\beta_{1p} \geq 0$ and $\beta_{2p} \geq 0$: higher current prices increase excess supply.

¹⁰Also notice that underground storage capacity is not included in the estimation (e.g. equation 26), as data on storage capacity are only available on a monthly basis as from 1993, whereas our dataset covers April 1986 to March 2005, thus resulting in a lack of information for almost one third of the period considered. Moreover, those data show little variability. From March 1993 to March 2005, underground storage capacity increase amounts to .03% only. Finally, there is no empirical evidence of saturation (see Section 2).

4. $\beta_{1T} \leq 0$ and $\beta_{2T} \geq 0$: higher temperatures in summer decrease excess supply (air-conditioning causes higher demand by electric utilities), and higher temperatures in winter increase excess supply (less heating).
5. $\beta_{1Y} \leq 0$ and $\beta_{2Y} \leq 0$: GDP essentially affects demand and thus must impact excess supply negatively.
6. $r \geq 1$ and $c \geq 0$: using equation (27), we can estimate r as $\hat{\beta}_{3p} - 1$ and c as $\hat{\beta}_3^0 / \hat{\beta}_{3p}$.

The first two tests challenge our annual approach; the others question standard economic intuition.

A “year” y is composed of two six-month periods and starts with the “summer” (accumulation period) and finishes with the “winter” (drainage period). Using monthly data, we calculated the two consecutive six-month periods that *maximize* the variability of the stock variation (in other terms that smooth the cycle the least possible) over the sample. The best aggregates we find are 2nd and 3rd quarters for the summer, 4th quarter and 1st quarter of the subsequent year for the winter. Price and temperature averages as well as GDP are calculated for the same periods.

A more complete dynamic analysis of the yearly cycle using original monthly data would be inextricable (in particular, identification problems due to the multiplication of seasonal, i.e. month-specific, effects). Still, the simplicity argument apart, one may question the validity of the proposed time aggregation. Remark that if p_S^i is the gas price for the i th summer month ($i = 1, \dots, 6$), and if r and c are, respectively, the opportunity cost of capital and the carrying costs over six months, then, due to continued storage, arbitrage predicts that the price in the i th winter month p_W^i equals $(1 + r)(p_S^i + c)$. The six equations that we obtain as i varies can be summed up and divided by six to yield $p_W = (1 + r)(p_S + c)$, in which the prices are the season averages in the considered year. Moreover, if we assume that, each month, excess supply depends linearly on the current price, the current temperature and the current GDP, then the linear specification of excess demand is also preserved by time aggregation.

The dataset covers April 1986 (year in which deregulation started) to March 2005. Table 3 in Appendix presents descriptive statistics and sources.

Results. We use 3SLS, a method that estimates the covariance matrix of the shocks and does not require normal distributions of the shocks for consistency. Test 1 is passed in a first 3SLS run, so we impose $\beta_4^0 = 0$ and $\beta_{4\Delta} = -1$ in the final estimation. This hardly changes the estimates. As for

Test 2: the correlation is $-.299$ with standard error $.185$ (corresponding to a probability of $.126$ under the null hypothesis). Though catch-up effects seem not to be absent, their magnitude is low.

Equation (27) is replaced by

$$p_{yW} = \beta_3^0 + \beta_{3p}p_{yS} + \varepsilon_{y3}, \quad (29)$$

where ε_{y3} represent winter shift (correlation with ε_{y1} is allowed, meaning that the shift may be partially anticipated). See Table 1.

| Equation | Coeff. | St. Err. | z | $P > z $ |
|-----------------------|---------------------|--------------------|-------|-----------|
| $\Delta_{yS} = \dots$ | | | | |
| Constant | 1.57×10^7 | 6.82×10^6 | 2.30 | .022 |
| p_{yS} | 2.50×10^5 | 1.46×10^5 | 1.72 | .086 |
| Y_{yS} | -35.4 | 93.2 | -0.38 | .705 |
| T_{yS} | -2.29×10^5 | 1.05×10^5 | -2.18 | .029 |
| $\Delta_{yW} = \dots$ | | | | |
| Constant | -5.51×10^6 | 1.78×10^6 | -3.08 | .002 |
| p_{yW} | 2.58×10^5 | 1.10×10^5 | 2.33 | .020 |
| Y_{yW} | -336 | 91.6 | -3.66 | .000 |
| T_{yW} | 1.35×10^5 | 4.76×10^4 | 2.84 | .005 |
| $p_{yW} = \dots$ | | | | |
| Constant | -.168 | .181 | -0.93 | .351 |
| p_{yS} | 1.10 | .068 | 1.47* | .144* |
| *Tested against 1. | | | | |

Table 1. Core equations of the seasonal storage model.

Tests 3, 4 and 5 are passed successfully. The estimate for the interest rate is $\hat{r} = 10\%$, whereas there is no significant evidence of the impact of storage unit cost (\hat{c} is not significantly different from 0). Overall, the theory we exposed is not contradicted by the data.

6.2 Evaluation of the welfare effects of price policies

To evaluate welfare, the structural parameters estimated under the assumption that markets are competitive enable us to calculate the equilibrium under several scenarios. Once domestic production and net import parameters are known, demand parameters are calculated using accounting identity (equation 3). We ran regressions of domestic production and net imports on the current price. The results are not stable (exclusion of a particular year or inclusion of normally irrelevant explanatory variables have an impact

on the estimates) and tend to exhibit excess price elasticity (derived effect of price on demand has the wrong sign). This happens whether we include the production equations in the previous system (3SLS) or estimate them separately (OLS/2SLS). In contrast, the four core equations (25)-(28) give similar estimates with the three methods.

One obvious reason for this is that production largely depends on productive capacity, which we thus proxied with the number of active wells given by the EIA. This indicator does not account for the extreme heterogeneity between wells; nevertheless, the predicted price elasticities are now lower, indicating that we are more in line with the short term logic we put forward. Remark that the dynamics of this kind of data is extremely hard to capture in a model.¹¹ We restricted the sample to years 1993 to 2005, the period between 1986 and 1992 having a strong influence on the estimates. (See Table 4 in Appendix.) The small sample does not warranty precise estimates. In accordance with economic intuition, the implied price elasticity of demand is now negative; the impact of prices on domestic production is not significant, whereas imports are price-inelastic.

To focus on price policies, we reason on the average year (sample average temperature, GDP, number of wells). Linear demand and supply functions are integrated to give linear-quadratic utility and cost functions. We compare three scenarios:

1. Pure competition.
2. The optimal price cap for residents (consumers and domestic producers) with winter efficient rationing (see Subsection 5.2).
3. The residents' optimum: tariffs only, no rationing (see Subsection 5.3). We calculate optimal τ_S and associated equilibrium prices and quantities (see Subsection 5.4).

The total maximum surplus is set by convention to 0 in Table 2;¹² other surpluses are given as differences with the maximum. The optimal price cap is overall less distortionary than optimal tariffs; the latter are nevertheless, by definition, more attractive for residents. The optimal tariffs are very large (about \$7 per MMcf) and do more than halve the import price. This effect is due to the relative inflexibility of imports. The price cap discourages storage, as predicted, and more than tariffs, whose effect is ambiguous in theory.

¹¹See the classic Balestra and Nerlove (1966) on the modelling of demand for natural gas with consideration of the stock of appliances.

¹²The value found by integration of the demand and supply functions is B\$ 6.21. However this calculation involves extrapolating the functions well beyond the sample.

| Scenario | Perfect comp. | Opt. price cap | Opt. tariffs |
|-------------------|---------------|----------------|--------------|
| Total surp./year | 0 | −1.06 | −1.84 |
| Dom. surp./year | −12.7 | −11.5 | −10.4 |
| Stocks (10^6) | 1.65 | 1.47 | 1.60 |
| Summer | | | |
| Import price | 2.49 | 1.29 | 1.23 |
| Domestic price | 2.49 | 1.29 | 7.51 |
| Tariff | 0 | 0 | 6.28 |
| Winter | | | |
| Import price | 2.56 | 1.6 | 0.91 |
| Domestic price | 2.56 | 1.6 | 8.08 |
| Tariff | 0 | 0 | 7.16 |

Table 2. Comparison of three price policies.

Quantities in MMcf, prices in \$/MMcf, surpluses in M\$.

A limit to this exercise is that, in accordance with the estimation results, the optimal policy should be conditional on observables like temperature or GDP. More importantly, though the elasticity of imports seems low and thus “justifies” high tariffs, in the long run elasticity, through investment by producers to deliver gas towards more profitable regions, is certainly much greater. The extent of US market power over external providers is also hard to measure. In any case, the modest extra surplus calculated could be seen to be upper bounds of the potential benefits.¹³

7 Conclusion

The model enabled us to expose a comprehensive view of seasonal natural gas markets. The analysis shows that most policies in favor of consumers (price caps, rationing, taxes, cross subsidies) can be advantageously replaced by a parsimonious use of tariffs. The estimates based on the US data over

¹³The interplay between tariffs and price cap was addressed by Wright and Williams (1982b), who analyze public policies as a response to an oil supply disruption due to random shocks. However, in the Wright-Williams model, the relative effects of the two price policies, namely the price cap and the import tariffs, are difficult to disentangle as embedded in a very complex dynamic game, with government and the private sector interacting strategically. The overall results, obtained by simulations, are that, if it is impossible to impose an optimal tariff, a price ceiling could alleviate the consequences of supply disruption, thus improving domestic surplus, but even mild price controls can excessively reduce private storage. Nevertheless, as the authors point out, these results are sensitive to choices of the parameters used in the simulations and the constraints on the set of feasible policies.

1986-2005 were used to calculate the potential surplus gains the country could achieve. Given the relatively low values found and the uncertainty attached to the parameters, no intervention through tariffs is a defensible policy. This is in line with current US policy. Under the North American Free Trade Agreement, all gas tariffs were removed between the United States and Canada in 1996, and between the United States and Mexico in 1999. In general, gas has typically been very lightly taxed compared to oil, not only because it is not much used in transport (where the bulk of oil taxation falls), but also to encourage a shift on dependence away from oil and to support the development of the necessary infrastructure (Newbery, 2005). This supports the view that when a state wants to exert monopsony power, it only distorts import price leaving unaffected national prices.

Our model is focused on liberalized gas markets, but it can be used as a building block when one considers regulatory issues such as access to storage or transportation charges.

If the storage capacity is saturated at the end of the summer, the endogenous storage charge generates a scarcity rent. Under competition, allowing usage rights with regulated storage prices or leaving prices unregulated only changes the allocation of the rent, since the prices and quantities exchanged and stored are unaffected. The rent is simply left to those who detain the right to store. Both usage rights with regulated storage prices and unregulated prices lead to the social optimum in which the scarcity rent is the marginal welfare loss due to the constraint. This equivalence is only true in the short run; in the long run investment becomes a serious issue. For regulators, the balance between preserving incentives to invest (rents) and fighting market power requires information on the long run marginal cost, whose evaluation is enormously complicated by the huge heterogeneity of possible sites (location, geological characteristics). Though rents are not per se proofs of noncompetitive behavior, the regulator must be able to distinguish a case of true scarcity from an abuse of market power via voluntary restriction of supply. In this respect, the caution of FERC in allowing gas companies to use market-based rates for storage access instead of regulated tariffs, is understandable.¹⁴

Figure 7 shows an example in which the seasonal approach can be eas-

¹⁴FERC Order 636 opens access to gas storage at regulated prices that comprise a fixed capacity charge (reservation or booking fee) and a commodity charge (according to usage). Market-based tariffs can be applied where sufficient competition between facilities is demonstrated. To obtain market-based prices, large pipeline companies have to argue that industry restructuring and network interconnections have effectively broadened the market for storage beyond some narrow geographic area where that company predominates, and that prospective storage customers actually have many good alternatives.

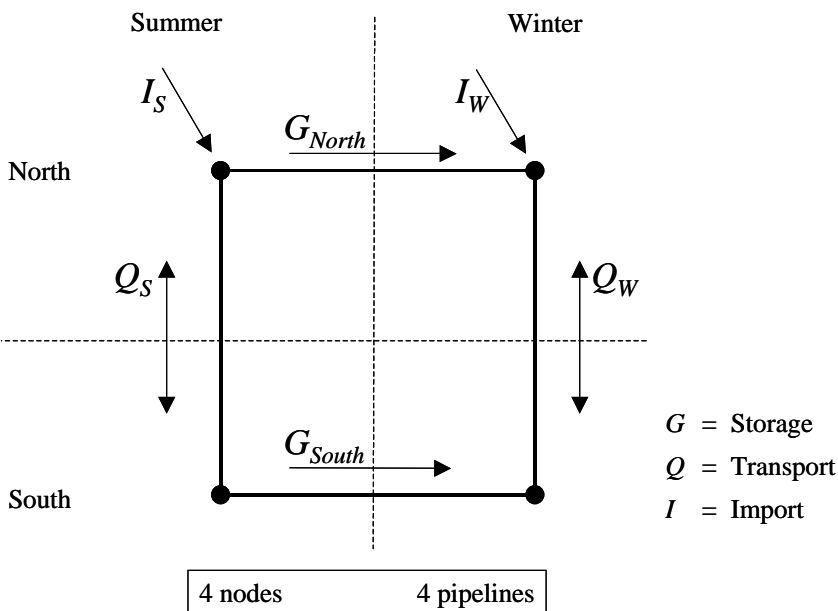


Figure 7: Equivalence between Storage and Transportation.

ily integrated into a gas transportation network. The picture distinguishes nodes as a combination of two characteristics: season (summer or winter) and location (North or South). All imports come from the North. Storage is only transportation from one node to another at the same location but in the following season. The theory of nodal prices (e.g. Cremer *et al.*, 2003) can be applied: one can try to implement the first best allocation with marginal cost pricing, or calculate the Ramsey charges, if the objective is to let users, rather than society as a whole, finance the infrastructure. The case of “counterflows” can also be integrated.

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A Proofs

A.1 Proof of Proposition 1

The transversality condition imposes that the stocks become necessarily null in finite time. We show by contradiction that from then on, stockholding remains seasonal (holding stock two or more successive periods is impossible).

Suppose that there is an integer $m \geq 3$ such that stocks are null at the end of $y\sigma$, strictly positive at the end of the periods $n^j(y\sigma)$ for $1 \leq j < m$, and null at the end of $n^m(y\sigma)$. The stock at the end of period $n^j(y\sigma)$ for $j \leq m$ is

$$G_{n^j(y\sigma)} = \sum_{i=1}^j \Delta_{n^i(y\sigma)}[N^i[p_{y\sigma}]], \quad (30)$$

Given that the economy is regular (see definition 2), for all j such that $3 \leq j \leq m$

$$G_{n^j(y\sigma)} - G_{n^2(y\sigma)} = \sum_{i=3}^j \Delta_{n^i(y\sigma)}[N^i[p_{y\sigma}]] > \sum_{i=1}^{j-2} \Delta_{n^i(y\sigma)}[N^i[p_{y\sigma}]] = G_{n^{j-2}(y\sigma)}. \quad (31)$$

This equation displays a contradiction for $j = m$: the LHS is negative, while the RHS is positive.

A.2 Proof of Proposition 2

1. The parallel evolution of the two prices \bar{p}_S and \bar{p}_W is due to the no-arbitrage equation ($\frac{\bar{p}_W}{1+r} = \bar{p}_S + c$) satisfied whenever storage is positive, and to the fact that the constraint binds during peaks: $\bar{p}_W = \bar{p}$. To see that storage is discouraged, observe that demand during summer increases whereas production decreases (as current price is decreased). This immediately implies that in winter demand exceeds supply and consumers are rationed.

2. We start from the unconstrained competitive equilibrium. Let us choose $\bar{p} = p_W - dp$, with small $dp > 0$. We get $\bar{p}_W = \bar{p}$ and $\bar{p}_S = p_S - \frac{dp}{1+r}$. The impact on the consumer's surplus during summer is positive and of first order with respect to dp since they only benefit from the lower price. During winter, on the one hand they benefit from lower prices (first-order effect), but on the other hand, demand is increased (first-order) while supply is decreased (negative first-order effects on production *and* storage). This rationing only provokes second-order effects on winter surplus, therefore the benefits dominate the loss for small dp .

A.3 Proof of Proposition 3

Equation (21) holds in the competitive and the monopsony allocations, implying that q_S^C and q_W^C are both higher or lower in the latter. We show by contradiction that they are lower. Assume that q_S^C and q_W^C are higher. The LHS of equations (22) and (23) decrease, meaning that q_S^I and q_W^I decrease. Similarly, equations (19) and (20) imply that q_S^D and q_W^D also decrease. This contradicts equation (24).

Remark that $G = q_S^D + q_S^I - q_S^C$. Depending on which of production and consumption in summer is most impacted by the government policy, G increases or decreases with respect to the competitive benchmark. One can easily verify with a linear version of the model that both cases are possible.

A.4 Descriptive statistics

We used the monthly data published by the EIA, aggregated into two seasons per 12-month period from April 1986 to March 2005. Temperature data are from the National Climatic Data service (US Department of Commerce), whereas GDP quarterly data are obtained from the Bureau of Economic Analysis (US Department of Commerce).

| Variable | Unit | Mean | Std. Dev. | Min. | Max. |
|----------------|--------|----------|-----------|----------|--------------------|
| GDP_S | B\$ | 8313 | 1439 | 6262 | 10846 |
| GDP_W | B\$ | 8317 | 1436 | 6265 | 10838 |
| Wells | # | 307129.7 | 49949.19 | 241527 | 401480 |
| T_S | °F | 62.77842 | .6637795 | 61.57 | 63.88 |
| T_W | °F | 44.41 | .145406 | 41.97 | 46.71 |
| Δ_S | MMcf | 1638388 | 325292.7 | 1160000 | 2262996 |
| Δ_W | MMcf | -1649048 | 294352.6 | -2323528 | -1163000 |
| Dom. prod. S | MMcf | 9331938 | 621662 | 7970839 | 1.01×10^7 |
| Dom. prod. W | MMcf | 9600006 | 303795 | 8898230 | 1.01×10^7 |
| Net imp. S | MMcf | 1282275 | 453669 | 469932 | 1930174 |
| Net imp. W | MMcf | 1164139 | 505577 | 261408 | 1819766 |
| p_S | \$/Mcf | 2.46 | 1.13 | 1.46 | 5.42 |
| p_W | \$/Mcf | 2.53 | 1.22 | 1.56 | 5.57 |

Table 3. Descriptive statistics.

Note: MMcf = one million cubic feet, Mcf = one thousand cubic feet. GDP in annual value.

A.5 Production and imports

| Equation | Coeff. | St. Err. | z | $P > z $ |
|-------------------|---------------------|--------------------|-------|-----------|
| Summer dom. prod. | | | | |
| Constant | 8.60×10^6 | 9.18×10^5 | 9.37 | .000 |
| p_{yS} | -1.40×10^5 | 1.27×10^5 | -1.10 | .280 |
| Wells | 4.59 | 3.66 | 1.25 | .217 |
| Summer net imp. | | | | |
| Constant | 1.05×10^6 | 1.44×10^5 | 7.29 | .000 |
| p_{yS} | 2.08×10^5 | 4.66×10^4 | 4.46 | .000 |
| Winter dom. prod. | | | | |
| Constant | 1.08×10^7 | 6.47×10^5 | 16.71 | .000 |
| p_{yW} | 9070 | 8.47×10^4 | 0.11 | .915 |
| Wells | -3.18 | 2.58 | -1.23 | .226 |
| Winter net imp. | | | | |
| Constant | 1.19×10^6 | 1.31×10^5 | 9.09 | .000 |
| p_{yW} | 1.92×10^5 | 4.03×10^4 | 4.78 | .000 |

Table 4. Domestic production and imports.