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Strategic Storage and Market Power in the Natural Gas Market

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Abstract

In a competitive setting, storage is traditionally used to smooth production costs or face demand variations. However, oligopolistic sellers can also use inventories as a commitment tool. We analyze strategically motivated storage in a model where, as in the European gas market, both producers and suppliers have market power. In this two-tier oligopolistic structure, storage allows suppliers not only to preempt future demand, but also to counter producers' market power. This, in return, exerts a positive externality on rival suppliers, who benefit from lower spot prices, and downstream competition increases. Strategic storage results from arbitrating between these antagonistic effects.

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1 Introduction

The purpose of our paper is to analyze strategically motivated storage in the presence of imperfect competition at several levels of the supply chain. We show that the basic intuition according to which strategic storage consists in acquiring a leadership over rivals by preempting future demand does not hold unequivocally. We disentangle different purely strategic effects of inventories and analyze their interaction. Modeling the industry structure as a two-tier oligopoly provides innovative insights into the impact of storage on imperfectly competitive firms' incentives and behavior. In addition to this theoretical contribution, the choice of this particular market structure provides a framework to understand better the specific features of competition in the European market for natural gas.

Much of the literature devoted to storage considers a competitive environment where storage contributes to matching stochastic supply and demand. The primary focus of this literature is to investigate price dynamics. Kirman and Sobel (1974)

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showed that storage introduces an intertemporal dependence between each period's price-quantity strategies. Williams and Wright (1991) provided a comprehensive analysis of storage in an economy facing random shocks, using stochastic dynamic programming and numerical simulations. Literature on seasonal storage, where demand variations follow a regular pattern, is rather scarce. Chaton, Creti and Villeneuve (2005) proposed a model encompassing the issues of seasonal storage and resource exhaustibility, with perfectly competitive production and storage.

Actually, as we will show, the role of storage and the incentives to use it depend crucially on the structure and the degree of competition in the industry.

Storage in a competitive environment: When suppliers of a storable good are perfectly competitive and face variations in the cost of producing or purchasing the good, they will use storage to smooth their costs. In a two-period model where first-period and second-period costs are respectively $\underline{p_s}$ and $\overline{p_s}$, the profit-maximization program of a supplier gives the following no-arbitrage condition under no uncertainty (see Williams and Wright 1991 for the stochastic case):

$$\begin{cases} \underline{p_s} + c = \overline{p_s} \quad \textbf{and} \quad S \geq 0 \\ or \\ \underline{p_s} + c > \overline{p_s} \quad \textbf{and} \quad S = 0 \end{cases}$$

A competitive supplier will store a quantity such that he is indifferent between, on the one hand, buying or producing an additional unit in the first period and incurring holding costs, and on the other hand, buying or producing this additional unit in the second period.

This no-arbitrage condition, however, is only valid when suppliers are perfectly competitive and do not use storage for strategic purposes.

Storage with oligopolistic suppliers: Arvan (1985), Saloner (1987) and Pal (1991) first contributed to analyzing storage as a strategic tool. Saloner and Pal, as well as Mitraille and Moreaux (2007), consider a model with two production periods, where oligopolistic suppliers sell only in the final period. In a similar setting, Arvan analyzes the case where sales occur at both periods. In this context, stockpiling can be viewed as a commitment mechanism, since quantities previously produced and now in stock can be released to the market at no cost at any moment. By threatening to flood the market, an oligopolistic seller can effectively deter competitors from producing and, by this means, obtain a leader's market share. In this way, storage affects rivals' decisions in future periods.

Referring to the literature on dynamic games with irreversible commitment, which focuses on capacity-building, Arvan notes that inventory offers a more credible commitment than capacity in the short run:

> "the marginal cost of supplying an additional unit out of finished product inventory is zero as long as inventory stock is positive, while there remains a positive marginal cost of supplying an additional unit out of production, even when some capacity is idle" (p.570).

On the other hand, since sales out of inventory deplete the inventory stock, in the long run the commitment effect disappears.

In Arvan's model there is no efficiency motive for carrying inventories, because the marginal cost of production is assumed to be constant. This eliminates the intrinsic rationale for storage that exists in the case with convex costs, where smoothing production reduces costs. With linear costs, carrying inventories yields no efficiency gain with respect to producing immediately, and it is costly. Therefore a supplier will hold inventories only if it gives him the possibility to act as a leader in the second period and obtain a larger market share. But if both suppliers produce again in the second period they face the same marginal cost and, since they are symmetric, they will have identical sales. A supplier can only obtain a higher market share if he ceases producing and sells exclusively from his inventories, because his marginal cost becomes zero. In this sense, building large inventories is a means to preempt future demand. Though firms are symmetric and play simultaneously, Arvan proves the existence of asymmetric equilibria where one supplier holds large inventories and does not produce any more, thereby obtaining a leader's market share in the second period, while the other supplier does not build any inventories.

The case where both suppliers carry positive inventories cannot be an equilibrium of this game, since both firms would use storage to act as a leader. Symmetric equilibria without storage may exist, but there is no symmetric equilibrium with storage.

In a similar setting with convex production costs, Mollgaard, Poddar and Sasaki (2000) prove the existence of a symmetric equilibrium with storage (when the cost is sufficiently convex, but the game leads to a prisoner's dilemma, since both firms seek to acquire a leadership through storage, and they finally obtain smaller profits.

In this type of model, each firm would like to be the only one to store: in an asymmetric equilibrium, the firm who builds inventories obtains a higher profit. Unsurprisingly, if one supplier has a Stackelberg advantage on storage, he will choose an aggressive stockpiling strategy in order to preempt the second-period market.

Storage in a two-tier oligopoly: The case where both producers and suppliers have market power has virtually never been addressed in the literature about storage, except by Baranès, Mirabel and Poudou. However in their first model (2005) storage is treated as a necessary step of the production process instead of being an alternative to buying on spot. In another model (2007), they analyze the arbitrage between carrying inventories and buying on spot. Though this model is in many respects similar to ours, it assumes perfectly competitive production in the first period, while we assume producers behave strategically at each period when setting the spot price (possibly trying to deter storage). Therefore our results are quite different.

The intuition that strategic storage aims solely at preempting future demand does not hold any more in a setting where oligopolistic suppliers do not produce themselves but buy from oligopolistic producers on an intermediate ("spot") market. The spot price is influenced by storage decisions of suppliers: buying an additional unit in the first period and carrying it over into the next period instead of buying it in the second period pushes the first-period spot price up and the second-period spot price down. But since all rival suppliers buy at this spot price, they also benefit from price changes without incurring storage costs. Thus, when deciding on his inventories, a supplier has to take into account two effects:

- storage can reduce producers' market power by preventing them from discriminating perfectly between first-period and second-period sales on the spot market. By giving the supplier an opportunity to arbitrate between the two periods, it reduces his purchasing costs from producers.
- storage exerts a positive externality on rival suppliers, who will benefit from a lower spot price in the second period. This will increase downstream competition and lower revenues on the second-period downstream market.

Two-tier oligopoly models yield original results compared to the existing literature with a single oligopolistic level. First, contrary to findings by Arvan (1985), we prove the existence of symmetric equilibria with positive storage even with constant marginal cost. Furthermore, the intuition that strategic storage consists simply in preempting future demand (so that each firm would like to store more than her rival) does not hold in a setting where storage exerts a positive externality on competitors through the channel of spot prices: on the contrary, a supplier achieves highest profits in an asymmetric equilibrium where he stores less than his rival. Similarly, if storage capacities are limited and suppliers are allocated capacity rights, the firm who obtains less capacities can make more profit than her rival.

The rest of the paper is organized as follows. Section 2 presents the model and derives the different equilibria. In section 3 we extend our results to the case where storage capacities are limited. Section 4 concludes. Proofs of all results appear in the appendix.

2 The model

We consider a setting where producers as well as suppliers are oligopolistic. Producers and suppliers compete à la Cournot, while final consumers are price-takers. This means that suppliers have market power on the downstream market, but they are price-takers with respect to producers on the intermediate market. To simplify, we assume that there is a single producer and two identical suppliers i and j. Storage is assumed to be operated by an independent firm.

Since our focus is strategic storage, we eliminate all classical motivations to carry inventories, such as uncertainty, production constraints or non-linearities in costs. The marginal production cost is constant (and set equal to zero).

The model has two periods[1], which can be interpreted as a low-demand period (summer) followed by a high-demand period (winter)[2].

[1] Chaton, Creti, Villeneuve (2005) show in a competitive setting with seasonal demand that in any equilibrium storage becomes seasonal (stocks are empty each year at the end of winter) in finite time and remains so. They obtain a succession of two-period cycles that are independent from each other. We will restrict to one such cycle.

[2] As for natural gas, it can be considered as a stylized fact that winter demand in Europe is three to four times higher than in summer.

Consumer demand Consumers are price-takers, their demand is elastic and lower in the first period than in the second period. Inverse demand functions are respectively: $\underline{p} = \underline{a} - \underline{X}$ and $\overline{p} = \overline{a} - \overline{X}$, where the non-stochastic demand parameters are such that $\underline{a} < \overline{a}$, and $\underline{X}$, $\overline{X}$ and $\underline{p}$, $\overline{p}$ denote sales and downstream prices at each of the two periods.

Suppliers Suppliers compete à la Cournot on the final market in both periods. They buy from the producer in the first (second) period on the intermediate market the quantities $\underline{k_i}$, $\underline{k_j}$ ($\overline{k_i}$, $\overline{k_j}$) at price $\underline{p_s}$ ($\overline{p_s}$). We assume that suppliers cannot sell on the intermediate market, they can only be buyers.

They can decide in the first period to carry inventories for subsequent sale. In the basic model, there are no constraints on storage capacities. The unit price of storage, c, is assumed to be constant and exogenous.

Producer The producer decides in each period the quantity ($\underline{K}$, then $\overline{K}$) he sells on the intermediate ('spot') market. Since he is monopolistic, it is equivalent to consider that he sets the price ($\underline{p_s}$, then $\overline{p_s}$).

The timing is the following :

- First period:
  - the producer decides on the spot market price $\underline{p_s}$
  - the suppliers decide simultaneously on the quantities $\underline{k_i}$, $\underline{k_j}$ they buy on the spot market, the quantities $\underline{x_i}$, $\underline{x_j}$ they sell immediately and the quantities s_i, s_j they store.
- Second period:
  - the producer decides on the spot market price $\overline{p_s}$
  - the suppliers can sell off inventory, they decide simultaneously on the quantities $\overline{k_i}$, $\overline{k_j}$ they buy on the spot market and their final sales $\overline{x_i}$, $\overline{x_j}$.

The game is solved by backward induction, to identify the subgame perfect equilibria, which can be defined as follows.

Definition 1 (Equilibrium). *An equilibrium of the game is a set*

$$\left\{\underline{p_s}, \underline{k_i}, \underline{k_j}, s_i, s_j, \underline{x_i}, \underline{x_j}, \overline{p_s}, \overline{k_i}, \overline{k_j}, \overline{x_i}, \overline{x_j}\right\}$$

such that:

- $\underline{p_s}$ *maximizes the anticipated profit of the producer over the two periods*
- *for* $m = i, j$ $\underline{k_m}$, s_m *and* $\underline{x_m}$ *maximize the anticipated profit of supplier* m *over the two periods, given the rival's choices and the spot price* $\underline{p_s}$
- $\overline{p_s}$ *maximizes the anticipated second-period profit of the producer given the inventories of the suppliers*
- *for m=i,j* $\overline{k_m}$, *and* $\overline{x_m}$ *maximize the second-period profit of supplier* m *given the inventories in stock, the rival's choices and the spot price* $\overline{p_s}$

2.1 Second-period subgame

Downstream competition between suppliers

Suppliers i and j compete à la Cournot on the downstream market, taking the spot price $\overline{p_s}$ as given.

In the second period, when a supplier chooses his purchases on the intermediate market and his downstream sales, the production and storage cost of units in stock has already been incurred, and their marginal cost is now zero. A supplier will not buy on spot before he has exhausted his inventories. The marginal cost of one unit sold in the second period becomes positive when sales exceed inventory holdings and the supplier buys on the spot market ($\overline{k_i} > 0$).

Supplier i maximizes his second-period profit:

$$\max_{\overline{x_i},\overline{k_i}} \Pi_i = (\overline{a} - \overline{x_i} - \overline{x_j})\overline{x_i} - \overline{p_s}k_i$$

$$s.t. \begin{cases} \overline{x_i} \geq 0, \\ \overline{k_i} \geq 0, \\ \overline{k_i} + s_i \geq \overline{x_i}. \end{cases}$$

The value of the rival's sales $\overline{x_j}$ depends on his inventories s_j. The best-response function $\overline{x_i}(\overline{x_j})$ of supplier i, given his rival's inventories s_j, is continuous but exhibits two kinks. This function also depends on supplier i's own inventories s_i.

We can describe this best-response function when the rival's inventory holdings s_j are relatively small:

- When s_i is small, i buys on the intermediate market and $\overline{x_i} = \frac{\overline{a}-\overline{x_j}-\overline{p_s}}{2} > s_i$.
- When s_i takes intermediate values, i sells exactly his inventories: $\overline{x_i} = s_i$.
- When s_i is large, i is left with redundant inventory: $\overline{x_i} = \frac{\overline{a}-\overline{x_j}}{2} < s_i$.

To summarize, as shown by Arvan (1985) there are nine possible types of Nash equilibrium in the second-period subgame where suppliers choose their purchasing and sales strategies. Each supplier can:

- sell less than his inventories,
- exactly exhaust his inventories,
- buy on the intermediate market to sell more than his inventories.

It can easily be shown that equilibria of this subgame where a supplier is left with redundant inventory can never be equilibria of the complete game. This relies on the two-period structure of the model: suppliers will never store more than their anticipated sales because these units will have no value at the end of the second period.

There are equilibria in this subgame where both suppliers sell exactly their inventories: they will not buy any additional quantities on spot, even if the producer were selling at marginal cost, because they already hold very large inventories. We can show (see Appendix) that choosing such inventories in the first period cannot be optimal. A supplier will always prefer to deviate, store less and buy an additional unit on spot in the second period, where the price is low because demand is small.

Lemma 1. *There are two possible sorts of equilibria:* asymmetric equilibria *where one supplier sells exactly his inventories while the other supplier buys additional quantities on spot, and* symmetric equilibria *where both firms exhaust their inventories and are buyers on the spot market.*

We use here the word "asymmetric" to refer to the behavior on the second-period spot market - buy or not buy - and not to inventory choices. We will now focus only on the subgames that correspond to an equilibrium in the complete game.

Upstream production decision

The producer faces demand $\overline{K} = (\overline{x_i}+\overline{x_j})-(s_i+s_j)$. He maximizes his second-period profit, taking suppliers' inventories as given:

$$\begin{aligned} \max_{\overline{K}} \overline{\Pi_p} &= \overline{p_s}\overline{K} \\ s.t. \quad & \overline{K} \geq 0. \end{aligned}$$

We obtain the second-period spot price $\overline{p_s}$ as a function of s_i, s_j. Clearly, this spot price decreases with suppliers' inventories.

2.2 First-period subgame

We shall first describe the generic problem of inventory choice for suppliers, before deriving the solutions corresponding to the different equilibria - symmetric and asymmetric - in the second-period subgame.

In the first period, both suppliers simultaneously choose their first-period sales and the level of inventories they carry into the second period. Since they take the first-period spot price $\underline{p_s}$ as given, the choices of sales and inventories are independent from one another. [3]

There are no initial inventories, so both firms face the same marginal cost $\underline{p_s}$ and first-period sales are the usual quantities under Cournot competition:

$$\begin{cases} \underline{x_i} = \underline{x_j} = \frac{\underline{a}-\underline{p_s}}{3} & \textbf{if} \quad \underline{p_s} \leq \underline{a} \\ or & \\ \underline{x_i} = \underline{x_j} = 0 & \textbf{if} \quad \underline{p_s} > \underline{a}. \end{cases}$$

Supplier i chooses his inventories to maximize his intertemporal profit:

[3] Note however that the fact that downstream sales occur also in the first period (contrary to many models in the literature, such as Saloner (1987), Pal(1991), or Mitraille and Moreaux (2007)) plays an important role here, in spite of cost linearity: the producer, who plays strategically, will take these sales into account when arbitrating between his current and future revenues to set the first-period spot price.

$$\begin{aligned}&\max_{s_i} \Pi_i = (\underline{p} - \underline{p_s})\underline{x_i} - (\underline{p_s} + c)s_i + (\overline{p} - \overline{p_s})\overline{x_i} + \overline{p_s}s_i \\ &s.t. \qquad s_i \geq 0,\end{aligned}$$

which can be restated as

$$\begin{aligned}&\max_{s_i} \Pi_i = -(\underline{p_s} + c - \overline{p_s})s_i + (\overline{a} - \overline{x_i} - \overline{x_j} - \overline{p_s})\overline{x_i} \\ &s.t. \qquad s_i \geq 0.\end{aligned}$$

Using the envelope theorem, when suppliers choose their optimal sales given the spot price $\underline{p_s}$, we can write the marginal effect on profit of carrying an additional inventory unit:

$$\frac{\partial \overline{\Pi_i}}{\partial s_i} = -(\underline{p_s} + c - \overline{p_s}) - \frac{\partial \overline{p_s}}{\partial s_i}\overline{k_i} - \frac{\partial \overline{x_j}}{\partial s_i}\overline{x_i}. \tag{1}$$

- The first term (*arbitrage effect*) is the direct effect on purchasing costs of buying one additional unit in the first period and storing it instead of buying it in the second period.
- The second term (*countervailing power effect*) is the effect on the spot price, which affects all units bought by supplier i on the second-period spot market.
- The third term (*reducing rival's costs effect*) is the effect on downstream sales $\overline{x_i}$ resulting from increased competition because the rival supplier benefits from the reduction in the spot price.

The existence of these effects relies on the assumption of imperfect competition at both production and supply levels. When suppliers can carry inventories, they can arbitrate between spot prices, therefore the producer cannot charge the monopoly price at each period; he has to decrease his second-period spot price with respect to the first-period price. Thus storage mitigates the producer's market power, which is beneficial for the firm that holds stock. But storage exerts an externality on rival suppliers, by modifying the intermediate market price, which is equally charged to the rivals. When making his storage choice, a supplier has to arbitrate between these effects. Typically, the second and third terms will not cancel out, which gives the following result:

Proposition 1 (Strategic yield of Storage). *In a two-tier oligopoly where downstream firms can hold stocks, the no-arbitrage condition between two periods, such that for positive inventories $\underline{p_s} + c = \overline{p_s}$, does not hold in general.*

The strategic yield of storage can be defined as

$$SYS = \underline{p_s} + c - \overline{p_s}.$$

It is positive when at equilibrium the marginal cost of purchasing and storing one unit in the first period is higher than the cost of buying it in the second period, which means that there is also a strategic motive for carrying inventories.

We will now separately analyze games leading to symmetric and asymmetric equilibria.

2.2.1 First-period subgame leading to a symmetric equilibrium

Here we assume that both suppliers buy on spot in the second period. This equilibrium is possible provided that

$$\begin{cases} s_i < \frac{\overline{a}-\overline{p_s}}{3} \\ s_j < \frac{\overline{a}-\overline{p_s}}{3} \end{cases}$$

Inventory choice

Let us briefly refer to the case when producers are perfectly competitive - which is similar to the case when suppliers are themselves producers, as in Arvan (1985). The spot price equals marginal production cost (c_p) and does not depend on inventories. Thus, when both suppliers buy on spot, their second-period downstream sales and profits do not depend on inventories either. The marginal profit gain from storing an additional unit is then negative, and no supplier will carry inventory:

$$\frac{\partial \overline{\Pi_i}}{\partial s_i} = -(c_p + c - c_p) = -c < 0.$$

Thus, in a two-tier model with perfectly competitive producers and linear production costs, there is no symmetric equilibrium with storage.

By contrast, if producers are oligopolistic, the second and third terms on the right-hand side of equation (1) are not equal to zero.

With one producer and two suppliers, this equation writes:

$$\frac{\partial \overline{\Pi_i}}{\partial s_i} = -(\underline{p_s} + c - \overline{p_s}) + \frac{3}{4}\overline{k_i} - \frac{1}{4}\overline{x_i}.$$

Therefore, as we show below, equilibria with positive inventories do exist.

Solving for the inventories of suppliers i and j, we obtain total inventories as a function of the first-period spot price $\underline{p_s}$.

Upstream production decision

In the first period the producer faces on the intermediate market a demand $\underline{K}$ equal to the sum of inventories $s_i + s_j$ and first-period downstream sales $\underline{x_i} + \underline{x_j}$.

He chooses his production (or, equivalently, his price, as assumed for clarity reasons) in order to maximize his intertemporal profit:

$$\begin{aligned} \max_{\underline{p_s}} \Pi_p \quad &= \underline{p_s}\underline{K} + \overline{p_s}\overline{K} \\ s.c. \qquad & \underline{K} \geq 0 \end{aligned}$$

The producer anticipates that inventories carried into the future will compete with his second-period sales and curtail his monopoly power in the second period. [4]

[4] This effect is in some way similar to the problem of the durable goods monopoly, where some consumers buy in the first period and will not buy again in the second period; here a part of the producer's first-period sales is destined to the second-period consumers, because of storage, and in the second period the producer faces only the residual demand. In Coase's model, because the good is durable, the monopolist cannot commit not to compete with himself for future sales, and he would prefer to lease; here storage prevents the producer from discriminating between sales destined to first-period and second-period consumers.

Therefore he is incited to discourage storage through a high first-period price. But he also wants to preserve his profit from sales in the first period. He faces a tradeoff. The four possible outcomes are the following:

- positive first-period sales and positive inventories (XS)
- positive first-period sales and no inventories (X0)
- no first-period sales and positive inventories (0S)
- no first-period sales and no inventories (00).

Actually, depending on the parameters - demand swing and storage cost - only some of these subgame equilibria can exist (for example, if the demand swing is very high, we cannot have positive first-period sales, because suppliers prefer storing all the quantities they bought to sell them in the high-demand period). The producer will choose the price that yields the equilibrium which is most profitable for him (see Appendix).

The equilibrium X0 with positive sales and no storage can be achieved in two ways: either the cost of storage is so high that when the producer sets his static monopoly price at each period there is no storage (blockaded), or in the first period the producer chooses to set a higher price than his static optimum in order to deter storage. Thus, observing no storage at equilibrium does not mean that its existence has no impact on firms' behavior and on prices. In addition, as we can see in this example, with higher prices and lower quantities than if storage were not available, the existence of storage is not necessarily welfare-improving [5].

If the storage cost is not too high, a symmetric equilibrium (XS) with storage exists. Interestingly, inventories can be carried at equilibrium even if consumer demand is identical in the two periods. In the setting we considered, the strategic effect of storage is always positive: suppliers carry more inventories than they would if they simply wanted to smooth their costs of purchasing from the producer: $\underline{p_s}+c > \overline{p_s}$. Another way to look at it is to note that spot prices are smoother than under the no-arbitrage condition, and if the storage cost is negligible, they are counter-cyclical.

2.2.2 First-period subgame leading to an asymmetric equilibrium

We will now assume that supplier j does not buy on spot in the second period while supplier i does. Remember that this equilibrium is only valid for a range of inventory values such that:

$$\begin{cases} s_i < \frac{\overline{a}-\overline{p_s}}{3}, \\ \frac{\overline{a}-\overline{p_s}}{3} < s_j < \frac{\overline{a}+\overline{p_s}}{3}. \end{cases}$$

[5] A parallel can be drawn with the literature on spatial discrimination. It is well-known that the possibility of transport between two areas with different demands can reduce welfare because the monopoly has to set the same price for both groups of consumers, which implies a distortion in each area with respect to the optimum without transport. Here, since the model is not spatial but temporal, in the second period the producer will set his profit-maximizing price, so the distortion can only occur in the first period, which means moving further away from the optimum.

Second-period downstream sales are:

$$\begin{cases} \overline{x_i} = \frac{\overline{a} - \overline{p_s} - s_j}{2}, \\ \overline{x_j} = s_j. \end{cases}$$

Now the sales of supplier j are completely inelastic to his opponent's sales: in this equilibrium, he is committed to sell exactly his inventories, which is similar to a first-mover advantage for second-period sales. Equation (1) gives the first-order condition of his profit-maximization program:

$$\begin{cases} \frac{\partial \overline{\Pi_j}}{\partial s_j} = -(\underline{p_s} + c - \overline{p_s}) - \frac{\partial \overline{x_i}}{\partial s_j} \overline{x_j} = 0 & \text{and} \quad s_j > 0 \\ \quad \text{or} \qquad \frac{\partial \overline{\Pi_j}}{\partial s_j} < 0 & \text{and} \quad s_j = 0 \end{cases}$$

Though inventories give him a leadership advantage in the second period, there is a countervailing effect: when j stores, this decreases the price on the second-period spot market, where only his rival buys. This effect on the spot price is purely detrimental to supplier j.

As for supplier i, the first-order condition of his profit-maximization program is:

$$\begin{cases} \frac{\partial \overline{\Pi_i}}{\partial s_i} = -(\underline{p_s} + c - \overline{p_s}) - \frac{\partial \overline{p_s}}{\partial s_i} \overline{k_i} = 0 & \text{and} \quad s_i > 0, \\ \quad \text{or} \qquad \frac{\partial \overline{\Pi_i}}{\partial s_i} < 0 & \text{and} \quad s_i = 0. \end{cases}$$

Since his rival does not buy on spot, if supplier i uses storage to lower the spot price, this does not have the adverse effect of reducing rival's costs. Therefore he could choose to store even though this will not give him a leadership advantage.

However, when taking into account the constraint on inventory values (see Appendix), we obtain a unique equilibrium where only supplier j carries inventories:

$$\begin{cases} s_i = 0, \\ \\ s_j = \frac{4}{23}(-\underline{a} + 2\overline{a} - 3c). \end{cases}$$

In such an asymmetric equilibrium, supplier j carries inventories to obtain leadership in the second period, while supplier i only buys on spot in the second period and carries no inventories.

2.3 Equilibria and profits

As for the existence of equilibria with storage, the two-tier oligopoly structure yields novel results compared to the existing literature, which are summarized in the following proposition:

Proposition 2.

- *In a model with a single oligopolistic level, there is no symmetric equilibrium with positive inventories. The only equilibria are asymmetric: only one supplier buys on spot, and only his opponent carries inventories. The sole motive for storing is preemption of future demand.*

- *In a two-tier oligopoly model, in addition of such asymmetric equilibria, there exists a symmetric equilibrium where both suppliers carry positive inventories and buy on spot.*

Now let us compare the profits of the "aggressive" supplier j and his rival i in an asymmetric equilibrium. One would expect that since supplier j's inventories give him a first-mover advantage for second-period sales, as a leader he will always make a bigger profit. Actually, this is not the case.

Proposition 3. *In an asymmetric equilibrium where only one supplier carries inventories and only his rival buys on spot in the second period, the supplier with no inventories can make a larger profit.*

When the demand swing is large, or when the storage cost is high (see Appendix), then supplier i, who does not store, makes a larger profit. Thus, assuming a two-tier oligopoly challenges the conventional views on strategic storage: supplier j's preemption strategy through storage is less profitable than his rival's strategy of purchasing large quantities on spot, where the price has been lowered by supplier j's storage behavior[6].

3 Capacity constraints on storage

In this section, we assume that total inventories cannot exceed a maximum value S_{max}. Since this constraint can be binding, additional assumptions are needed to determine how storage capacities will be allocated. We suppose that supplier i obtains a share x of total storage capacities, and his rival obtains the remaining share $1-x$. When choosing their inventories, suppliers are free to store up to their capacities or let some capacities idle.

3.1 Exogenous allocation of storage capacities

The game is similar to the basic model, and in this section we focus on symmetric equilibria where both suppliers buy on spot in the second period. The second-period subgame is identical to that of the previous section. We will now analyze the inventory choice in the first period. Depending on the total amount of storage capacities and on the allocation of capacity rights, both suppliers can be constrained, only one of them or none.

Case when both suppliers are constrained:

We suppose that

$$\begin{cases} s_i = xS_{max} \\ s_j = (1-x)S_{max} \end{cases}$$

[6] The same intuition explains why, in a Stackelberg variant of this model where one supplier can decide first of his inventories and commit to them, he will not use this advantage to build larger inventories than his rival, and will choose instead not to store.

The producer anticipates suppliers' first-period demand destined to storage and first-period downstream sales and he sets the corresponding profit-maximizing price. As usual, we derive equilibrium prices, quantities and profits. Analyzing how supplier i's profit varies with x, we obtain the following result.

Proposition 4. *When a supplier is allocated a share x of storage capacities while his rival obtains a share $(1-x)$, in an equilibrium where the constraint is binding for both, his profit is either strictly increasing or strictly decreasing with x.*

When $2c + 3S_{max} < \overline{a} - \underline{a}$, his profit increases strictly with x.

When $2c + 3S_{max} > \overline{a} - \underline{a}$, his profit decreases strictly with x.

The first case seems rather intuitive: a supplier is better off when he is less constrained than his rival. However, this is not always true. When total storage capacities S_{max} are not too small and the storage cost c is high relative to the demand gap between the two periods, a supplier makes a higher profit when he obtains less storage capacities[7]. When S_{max} is sufficiently small for his rival to be always constrained, the supplier's profit is maximum when $x = 0$, which means that he does not obtain any storage capacity.

Case when only one supplier is constrained:

We suppose that

$$\begin{cases} s_i < xS_{max} \\ s_j = (1-x)S_{max} \end{cases}$$

Supplier i's inventories are not constrained by his capacities, he plays his best response to $s_j = (1-x)S_{max}$.

Proposition 5. *In an equilibrium where the constraint is only binding for the rival, a supplier's profit can decrease when he is allocated more capacities, even though he does not utilize these capacities.*

Two opposite effects come into play: when the rival j is more constrained on storage, he has less opportunities to acquire the product at a lower cost, so he will be less aggressive on the second-period downstream market; but since he will purchase more on spot, this will push the spot price up, which is detrimental for supplier i who also buys on spot. The balance between these effects depends on the parameters.

Intuitively, when xS_{max} is large compared to the demand gap, supplier i does not need to buy much on spot, especially if storage is cheap (low c), so the impact of supplier j's inventories on the spot price will be of little importance to him: his profit

[7] The profit is maximum for the lowest value of x that is compatible with an equilibrium where both suppliers are constrained. When x is too low and the rival ceases to be constrained by $(1-x)S_{max}$, we obtain a new type of equilibrium where the supplier's profit is lower. Therefore $x = 0$ is not always the optimum, but for some parameters it can actually be, which means that a supplier achieves highest profits when he is not granted any capacities.

will tend to decrease with supplier j's inventories $s_j = (1-x)S_{max}$, and therefore increase with x[8].

Conversely, when the cost of storage is sufficiently high compared to the demand gap[9], buying on spot becomes relatively more profitable compared to building inventories. In this case, a supplier's profit in an equilibrium where only his rival is constrained by storage capacities is a strictly decreasing function of his own capacities.

Now we suppose that only supplier i is constrained while his rival is not:

$$\begin{cases} s_i = xS_{max} \\ s_j < (1-x)S_{max} \end{cases}$$

Proposition 6. *In an equilibrium where the constraint is only binding for one supplier and not for his rival, the supplier's profit can decrease when he is allocated more capacities while remaining capacity-constrained.*

This is the case when the cost of storage is sufficiently high compared to the demand gap [10]: storage is relatively less profitable compared to purchasing on spot, and supplier i would like to see his rival carry more inventory, in order to benefit from a lower spot price. When x decreases, supplier i's constraint is tightened while supplier j is not directly affected (the limit $(1-x)S_{max}$ is not binding for him), but since j plays his best response he will increase his inventories when i stores less. Supplier i will then benefit from a lower spot price.

When only one supplier is constrained and the rival is not, being constrained gives some sort of Stackelberg advantage: supplier i commits credibly to carry no more inventory than xS_{max}. The other supplier, who is not constrained, can only play his best response, and he will generally make a smaller profit.

3.2 Choice of storage capacities by an incumbent supplier

We will now consider the situation where one supplier has an advantage over his rival for the choice of storage capacities. This can be the case when an incumbent supplier owns a storage installation and offers an entrant the remaining capacities after having determined his own needs. We abstract here from any manipulation of the price of access to storage. Our focus is to examine the incentive for an incumbent supplier to reserve more capacities than he actually intends to use, and possibly foreclose access to storage by competitors.

As shown in the previous section, two cases must be separated:

- When $2c + 3S_{max} < \overline{a} - \underline{a}$, a supplier's profit is maximum when his capacity share is highest. He will reserve all capacities and leave none for his rival.

[8] Supplier i's profit is not necessarily a monotonous function of x, because in the constraint $s_i < xS_{max}$, both the total storage capacity and supplier i's share x come into play. If x is not very large, supplier i will still buy on spot and be sensitive to the spot price decrease induced by his rival's inventories $(1-x)S_{max}$, so his profit will decrease with x. His profit will increase with x only when x is sufficiently large.

[9] A sufficient condition is that $cs > \frac{-6175\underline{a}+4573\overline{a}}{21355}$.

[10] A sufficient condition is that $cs > \frac{-7311\underline{a}+6383\overline{a}}{20329}$.

- When $2c + 3S_{max} > \overline{a} - \underline{a}$, a supplier's profit is maximum when his capacity share is minimum. He will reserve as little capacities as possible and leave the rest for his rival, provided that his rival remains capacity-constrained.

In the first case, when storage capacities are scarce, the storage price is low and the demand gap is large, a supplier can have an incentive to overstate his inventory needs in order to prevent his rival from accessing to storage.

However, when seasonal fluctuations of demand are less marked, when the storage cost is high or when storage capacities become abundant, a supplier has just the opposite incentive. He will reserve for himself less capacities than he offers to his rivals, and he can even prefer to sell all available storage capacities to his competitors.

4 Conclusion:

In the European market for natural gas, storage is often viewed as an essential facility, which implies that access to storage is crucial for the development of competition. The traditional approach to third-party access tends to suppose that an incumbent is tempted to prevent entrants from using storage capacities, in order to preserve his market power. However, when taking into account the structure of the market, with imperfect competition in both production and supply, we show that a supplier owning a storage facility is not always interested in foreclosure. On the contrary, he might prefer to let his rival bear the costs associated with holding inventories, and benefit from the subsequent reduction of the spot market price.

New entrants often complain of the lack of transparency regarding availability of storage capacities: incumbent suppliers owning storage facilities allegedly reserve more capacities than they actually need. We show that this behavior can be rational, but only under certain circumstances. If market conditions change, so that seasonal demand fluctuations are moderate, storage capacities are large or the cost of storage is high, the incentives of an incumbent supplier are radically altered, and he wishes to encourage competitor's storage.

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Appendix

Proof of Lemma 1:

As shown by Arvan (1985), inventories introduce a kink in suppliers' best response, since the production cost of units in stock has already been incurred and their marginal production cost is now zero. A supplier compares the marginal revenue of his sales: $\overline{a} - 2\overline{x_i} - \overline{x_j}$ with his marginal cost of production: zero as long as $x_i \leq s_i$, then $\overline{p_s}$ if $x_i > s_i$. Each supplier can either sell more than, sell exactly or sell less than his inventories:

$$\begin{cases} \overline{x_i} & = \frac{\overline{a} - \overline{p_s} - \overline{x_j}}{2} > s_i & \text{if } \overline{x_j} < \overline{a} - \overline{p_s} - 2s_i \\ & = s_i & \text{if } \overline{a} - \overline{p_s} - 2s_i < \overline{x_j} < \overline{a} - 2s_i \\ & = \frac{\overline{a} - \overline{x_j}}{2} < s_i & \text{if } \overline{x_j} \geq \overline{a} - 2s_i \end{cases}$$

Obviously, building more inventories than one expects to sell is a dominated strategy, therefore equilibria where a supplier sells less than his inventories cannot be equilibria of the complete game.

We will now demonstrate that the case where both suppliers sell exactly their inventories cannot be an equilibrium. In effect, since the demand on the second-period spot market is zero, the producer has no market power and is willing to sell the first unit at its production cost. Therefore, a supplier will always be incited to deviate, store less and buy an additional unit on spot.

Let us assume that $\overline{x_i} = s_i, \overline{x_j} = s_j$. There are no spot sales in the second period, and the downstream price is $\overline{p} = \overline{a} - s_i - s_j$. In the first period, supplier i chooses his inventories by solving the following program:

$$\begin{array}{ll} \max_{s_i} \Pi_i = (-\underline{p_s} - c + \overline{a} - s_i - s_j)s_i \\ s.t. \qquad s_i \geq 0. \end{array}$$

Since his rival solves the same program, their inventories are identical:

$$s_i = s_j = \frac{1}{3}(\overline{a} - \underline{p_s} - c).$$

But the equilibrium with no spot sales in the second period requires that $\frac{1}{3}(\overline{a} - \overline{p_s}) < s_i = s_j < \frac{\overline{a}}{3}$. This implies $c + \underline{p_s} < \overline{p_s}$, which contradicts the fact that the producer enjoys market power in the first period while he is willing to sell at production cost in the second period.

Solving for equilibrium sales, we obtain the following equilibria.

Symmetric equilibria: When

$$\begin{cases} s_i < \frac{\overline{a} - \overline{p_s}}{3} \\ s_j < \frac{\overline{a} - \overline{p_s}}{3} \end{cases}$$

then both suppliers buy additional quantities on the intermediate market and their sales are identical:

$$\overline{x_i} = \overline{x_j} = \frac{\overline{a} - \overline{p_s}}{3}$$

Asymmetric equilibria: When

$$\begin{cases} s_i < \frac{\overline{a} - \overline{p_s} - s_j}{2} \\ \frac{\overline{a} - \overline{p_s}}{3} < s_j < \frac{\overline{a} + \overline{p_s}}{3} \end{cases}$$

then only supplier i buys additional quantities on the intermediate market and sales are:

$$\begin{cases} \overline{x_i} = \frac{\overline{a} - \overline{p_s} - s_j}{2} \\ \overline{x_j} = s_j \end{cases}$$

Proof of Propositions 2 and 3:

First-period subgame leading to a symmetric equilibrium: We solve backwards, starting with the equilibrium of the second-period subgame where both suppliers buy positive quantities on spot.

Sales and storage choices by suppliers: since the second-period Cournot game gives $\overline{x_i} = \overline{x_j} = \frac{1}{3}(\overline{a} - \overline{p_s})$, the producer faces the inverse demand $\overline{p_s} = \overline{a} - \frac{3}{2}(\overline{K} + s_i + s_j)$ when choosing his profit-maximizing second-period production, which yields second-period price: $\overline{p_s} = \frac{1}{2}\overline{a} - \frac{3}{4}(s_i + s_j)$.

Cournot competition between suppliers in the first period results in the following first-period downstream sales:

$$\begin{cases} \underline{x_i} = \underline{x_j} = \frac{\underline{a} - \underline{p_s}}{3} & \textbf{if} \quad \underline{p_s} \leq \underline{a} \\ \underline{x_i} = \underline{x_j} = 0 & \textbf{if} \quad \underline{p_s} > \underline{a} \end{cases}$$

Supplier i, who buys positive quantities on spot in the second period, chooses his inventories solving the following intertemporal profit-maximization program:

$$\begin{array}{ll} \max_{s_i} \Pi_i = -(\underline{p_s} + c - \bar{p}_s)s_i + (\bar{a} - \bar{x}_i - \bar{x}_j - \bar{p}_s)\bar{x}_i \\ s.t. \qquad s_i \geq 0 \end{array}$$

Supplier j also buys on spot and faces a similar program. Since both suppliers face the same spot price and storage cost, their storage choice is necessary identical. We obtain inventories as a function of the first-period spot price:

$$\left\{\begin{array}{ll} s_i = s_j = \frac{1}{24}(7\overline{a} - 12c - 12\underline{p_s}) & \textbf{if} \quad \underline{p_s} \leq \frac{1}{24}(7\overline{a} - 12c) \\ or & \\ s_i = s_j = 0 & \textbf{if} \quad \underline{p_s} > \frac{1}{24}(7\overline{a} - 12c) \end{array}\right.$$

Production choice by the producer: The producer faces demand $\underline{K} = \underline{x_i} + \underline{x_j} + s_i + s_j$, and chooses his first-period production (or equivalently, his price) to maximize his total profit on the two periods.

$$\max_{\underline{p_s}} \Pi_p = \underline{p_s}\underline{K} + \overline{p_s}\overline{K}$$

We have to distinguish whether suppliers' first-period sales and inventories are positive or equal to zero.

- Equilibrium XS: If first-period sales and inventories are positive, the demand the producer faces is $\underline{K} = \frac{1}{12}(8\underline{a} + 7\overline{a} - 12c - 20\underline{p_s})$. His optimal first-period price is $\underline{p_s} = \frac{1}{124}(32\underline{a} + 31\overline{a} - 12c)$. Equilibrium inventories and first-period downstream sales are:

  $$\left\{\begin{array}{l} s_i = s_j = \frac{1}{186}(-24\underline{a} + 31\overline{a} - 84c) \\ \underline{x_i} = \underline{x_j} = \frac{1}{372}(92\underline{a} - 31\overline{a} + 12c) \end{array}\right.$$

  A necessary condition on the storage cost is

  $$\frac{1}{12}(-92\underline{a} + 31\overline{a}) < c < \frac{1}{84}(-24\underline{a} + 31\overline{a})$$

  Note that when $\underline{a} = \overline{a}$, this condition writes : $c < \frac{7}{84}\underline{a}$, so an equilibrium with positive inventories can exist even when demand is identical in the two periods, as long as c is sufficiently small. The strategic effect of storage is strictly positive:

  $$\underline{p_s} + c - \overline{p_s} = \frac{1}{31}(2\underline{a} + 7c) > 0$$

  Note also that when the storage cost is sufficiently small ($c < \frac{1}{12}\underline{a}$), $\underline{p_s} - \overline{p_s} > 0$: the spot price is higher in the first period than in the second, high-demand period.

- Equilibrium 0S: If first-period sales are zero and inventories are positive, the demand the producer faces is $\underline{K} = \frac{1}{12}(7\overline{a} - 12c - 12\underline{p_s})$. His optimal first-period price is $\underline{p_s} = \frac{1}{60}(31\overline{a} - 12c)$. Equilibrium inventories and first-period downstream sales are:

$$\begin{cases} s_i = s_j = \frac{1}{30}(\overline{a} - 12c) \\ \underline{x_i} = \underline{x_j} = 0 \end{cases}$$

  Necessary conditions on demand and the storage cost to ensure that first-period sales are zero and inventories are positive are

$$\begin{cases} \overline{a} > \frac{60}{31}\underline{a} \\ c < \frac{1}{12}\overline{a} \\ c < \frac{1}{12}(-60\underline{a} + 31\overline{a}) \end{cases}$$

- Equilibrium X0: If first-period sales are positive and inventories are zero, the inverse demand the producer faces is $\underline{K} = \frac{2}{3}(\underline{a} - \underline{p_s})$. This equilibrium can arise either if storage is blockaded (X0B) or if it is deterred (X0D). In the first case, if the storage cost is sufficiently high, the producer can simply maximize his static monopoly profit, since there is no intertemporal tradeoff. We obtain the static outcome $\underline{K} = \frac{1}{3}\underline{a}$. A necessary condition on the storage cost to ensure that inventories are zero is

$$c > \frac{1}{12}(-6\underline{a} + 7\overline{a}).$$

  If the cost of storage is not high enough, the producer has to set a higher first-period price than his static monopoly price in order to deter storage. He will choose the smallest price that is compatible with zero inventories: $\underline{p_s} = \frac{7}{12}\overline{a} - c$. This equilibrium arises when

$$\frac{1}{12}(-12\underline{a} + 7\overline{a}) < c < \frac{1}{12}(-6\underline{a} + 7\overline{a}).$$

- Equilibrium 00: The last possible equilibrium features no first-period sales and no inventories. This equilibrium can always be attained ($\underline{p_s}$ just needs to be sufficiently high), but obviously it is dominated when another equilibrium coexists with it.

There can be one, several or no subgame equilibrium that is consistent with the values of the parameters. If several of them are possible, the producer chooses the one that gives him the biggest profit.

Finally, we obtain the following equilibria:

- If $\overline{a} < \frac{73}{31}\underline{a}$
  - If $c < \frac{1}{84}(-24\underline{a} + 31\overline{a})$, we have equilibrium XS
  - If $\frac{1}{84}(-24\underline{a} + 31\overline{a}) < c < \frac{1}{12}(-92\underline{a} + 31\overline{a})$: equilibrium X0D
  - If $c > \frac{1}{12}(-92\underline{a} + 31\overline{a})$: equilibrium X0B

- If $\frac{73}{31}\underline{a} < \overline{a} < \frac{73}{30}\underline{a}$
  - If $c < \frac{1}{12}(-73\underline{a} + 31\overline{a})$, we have equilibrium 0S
  - If $\frac{1}{12}(-73\underline{a} + 31\overline{a}) < c < \frac{1}{84}(-24\underline{a} + 31\overline{a})$: equilibrium XS
  - If $\frac{1}{84}(-24\underline{a} + 31\overline{a}) < c < \frac{1}{12}(-92\underline{a} + 31\overline{a})$: equilibrium X0D
  - If $c > \frac{1}{12}(-92\underline{a} + 31\overline{a})$: equilibrium X0B
- If $\frac{73}{30}\underline{a} < \overline{a} < \frac{15+\sqrt{465}}{15}\underline{a}$
  - If $c < \frac{1}{12}\overline{a}$, we have equilibrium 0S
  - If $\frac{1}{12}\overline{a} < c < \frac{1}{84}(-24\underline{a} + 31\overline{a})$: equilibrium XS
  - If $\frac{1}{84}(-24\underline{a} + 31\overline{a}) < c < \frac{1}{12}(-92\underline{a} + 31\overline{a})$: equilibrium X0D
  - If $c > \frac{1}{12}(-92\underline{a} + 31\overline{a})$: equilibrium X0B
- If $\frac{15+\sqrt{465}}{15}\underline{a} < \overline{a} < \frac{10}{3}\underline{a}$
  - If $c < \frac{1}{12}\overline{a}$, we have equilibrium 0S
  - If $\frac{1}{12}\overline{a} < c < \frac{1}{12}(\underline{a} + \sqrt{31}\sqrt{-\underline{a}^2 - 2\underline{a}\overline{a} + \overline{a}^2})$: equilibrium 00
  - If $\frac{1}{12}(\underline{a} + \sqrt{31}\sqrt{-\underline{a}^2 - 2\underline{a}\overline{a} + \overline{a}^2}) < c < \frac{1}{84}(-24\underline{a} + 31\overline{a})$: equilibrium XS
  - If $\frac{1}{84}(-24\underline{a} + 31\overline{a}) < c < \frac{1}{12}(-92\underline{a} + 31\overline{a})$: equilibrium X0D
  - If $c > \frac{1}{12}(-92\underline{a} + 31\overline{a})$: equilibrium X0B
- If $\overline{a} > \frac{10}{3}\underline{a}$
  - If $c < \frac{1}{12}\overline{a}$, we have equilibrium 0S
  - If $\frac{1}{12}\overline{a} < c < \frac{1}{12}(-12\underline{a} + 7\overline{a})$: equilibrium XS
  - If $\frac{1}{12}(-12\underline{a} + 7\overline{a}) < c < \frac{1}{12}(-92\underline{a} + 31\overline{a})$: equilibrium X0D
  - If $c > \frac{1}{12}(-92\underline{a} + 31\overline{a})$: equilibrium X0B

First-period subgame leading to an asymmetric equilibrium: We now suppose that only supplier i buys on spot in the second period, while supplier j simply sells off his inventories. Thus,

$$\begin{cases} \overline{x_j} = s_j \\ \overline{x_i} = \frac{1}{2}(\overline{a} - \overline{p_s} - s_j) \end{cases}$$

The producer faces the demand $\overline{K} = \frac{1}{2}(\overline{a} - \overline{p_s} - 2s_i - s_j)$ when choosing his profit-maximizing second-period production, which yields second-period spot price: $\overline{p_s} = \frac{1}{2}(\overline{a} - 2s_i - s_j)$.

Supplier i, who buys positive quantities on spot in the second period, chooses his inventories solving the following intertemporal profit-maximization program:

$$\begin{array}{ll} \max_{s_i} \Pi_i = -(\underline{p_s} + c - \overline{p_s})s_i + (\overline{a} - \overline{x_i} - \overline{x_j} - \bar{p_s})\bar{x}_i \\ s.t. \qquad s_i \geq 0 \end{array}$$

which yields his best response:

$$\begin{cases} s_i = \frac{1}{6}(3\overline{a} - 4c - 4\underline{p_s} - 3s_j) & \text{if } \underline{p_s} \le \frac{1}{4}(3\overline{a} - 4c - 3s_j) \\ s_i = 0 & \text{if } \underline{p_s} > \frac{1}{4}(3\overline{a} - 4c - 3s_j) \end{cases}$$

Supplier j, who does not buy on spot in the second period, solves a similar program, which yields his best response:

$$\begin{cases} s_j = \frac{1}{6}(3\overline{a} - 4c - 4\underline{p_s} - 2s_i) & \text{if } \underline{p_s} \le \frac{1}{4}(3\overline{a} - 4c - 2s_i) \\ s_j = 0 & \text{if } \underline{p_s} > \frac{1}{4}(3\overline{a} - 4c - 2s_i) \end{cases}$$

Solving for equilibrium inventories, in the case they are both positive, we obtain:

$$\begin{cases} s_i = \frac{1}{10}(3\overline{a} - 4c - 4\underline{p_s}) \\ s_j = \frac{2}{15}(3\overline{a} - 4c - 4\underline{p_s}) \end{cases}$$

But the optimal choice of $\underline{p_s}$ is not compatible with the constraint on inventory values for an asymmetric equilibrium (the producer wants to set a high price, and j will not be able to store enough for an asymmetric inventory). Thus we have to look for an equilibrium where only supplier j carries inventories:

$$\begin{cases} s_i = 0 \\ s_j = \frac{1}{6}(3\overline{a} - 4c - 4\underline{p_s}) \end{cases}$$

Finally, we solve for the first-period spot price that maximizes the producer's profit, and we obtain a unique equilibrium: $\underline{p_s} = \frac{1}{92}(24\underline{a} + 21\overline{a} - 20c)$

$$\begin{cases} s_i = 0 \\ s_j = \frac{1}{6}(-\underline{a} + 2\overline{a} - 3c) \end{cases}$$

The necessary condition on the storage cost is

$$max(0, \frac{1}{20}(-68\underline{a} + 21\overline{a}) < c < \frac{1}{60}(-20\underline{a} + 17\overline{a}).$$

We see that in this asymmetric equilibrium, only one supplier does carry inventory, while his opponent is the only one who buys on spot (Proposition 2).

Let us compare the profits of supplier i, who does not store but buys on spot, and j, who stores. The profit of i is higher when $c > \frac{-44\underline{a}+(111-46\sqrt{3})\overline{a}}{132}$. If the demand swing is moderate ($\overline{a} < \frac{44}{3+5\sqrt{3}}\underline{a} \approx 3.77\underline{a}$), supplier i makes more profit only when the storage cost is higher than this value. If the demand swing is large, this value falls outside the validity range of values of c, thus supplier i always makes a larger profit (Proposition 3).

Proof of Propositions 4, 5, and 6:

Case when both suppliers are constrained: We suppose that

$$\begin{cases} s_i = xS_{max} \\ s_j = (1-x)S_{max} \end{cases}$$

The producer faces the demand $\underline{K} = \underline{x_i} + \underline{x_j} + K_{max}$, and chooses the profit-maximizing first-period production $\underline{K} = \frac{1}{6}(2\underline{a} + 3S_{max})$. We can compute and compare the equilibrium profits of suppliers i and j.

$$\Pi_i - \Pi_j = (x - \frac{1}{2})(-\underline{a} + \overline{a} - 2c - 3S_{max}).$$

Therefore, the supplier who obtains more capacities makes a larger profit if and only if $\overline{a} - \underline{a} > 3S_{max} + 2c$.

The same condition holds for the choice of storage capacities:

$$\frac{\partial \Pi_i}{\partial x} = \frac{1}{2} S_{max}(-\underline{a} + \overline{a} - 2c - 3S_{max}).$$

This means that supplier i's profit is an increasing function of his available capacity x when this condition is verified, and a decreasing function of x when the opposite holds (Proposition 4).

Case when only one supplier is constrained: We suppose that only supplier j is constrained:

$$\begin{cases} s_i < xS_{max} \\ s_j = (1-x)S_{max} \end{cases}$$

Supplier i's inventories are not constrained by his capacities, he plays his best response to $s_j = (1-x)S_{max}$.

$$s_i = \frac{1}{33}(14\overline{a} - 24c - 24\underline{p_s} - 15(1-x)S_{max}).$$

In the case first-period downstream sales are positive, the producer faces the first-period demand

$$\begin{aligned} \underline{K} &= \underline{x_i} + \underline{x_j} + s_i + s_j \\ &= \tfrac{2}{33}(11\underline{a} + 7\overline{a} - 12c - 33\underline{p_s} + 9(1-x)S_{max}) \end{aligned}$$

He chooses the profit-maximizing first-period production $\underline{K} = \frac{1}{651}(181\underline{a} + 65\overline{a} - 348c + 261(1-x)S_{max})$. We can compute the derivative with respect to x of the equilibrium profit of supplier i to see whether his profit increases with available capacity.

$$\frac{\partial \Pi_i}{\partial x} = \frac{1}{47089} S_{max}(-6175\underline{a} + 4573\overline{a} - 21355c - 24183(1-x)S_{max}).$$

A sufficient condition for the profit to be a strictly decreasing function of x is $-6175\underline{a} + 4573\overline{a} - 21355c < 0$. When the storage cost is sufficiently high compared to the demand gap, the profit of the supplier who is not constrained decreases when he is granted more storage capacities and his rival is granted less capacities (Proposition 5).

Now let us suppose that only supplier i is constrained:

$$\begin{cases} s_i = xS_{max} \\ s_j < (1-x)S_{max} \end{cases}$$

After solving the model in a similar way as previously, we compute the derivative with respect to x of the equilibrium profit of supplier i.

$$\frac{\partial \Pi_i}{\partial x} = \frac{1}{47089} S_{max}(-7311\underline{a} + 6383\overline{a} - 20329c - 41553xS_{max}).$$

A sufficient condition for the profit to be a strictly decreasing function of x is $-7311\underline{a} + 6383\overline{a} - 20329c < 0$. When this condition holds, the profit of the supplier who is constrained decreases when he is granted more storage capacities and his rival is granted less capacities (Proposition 6).