Real assets are usually valued by computing the stream of profits they can bring to a price-taking firm in a liquid market. This method ignores market fundamentals by assuming that all the relevant information is included in the spot price. Our article analyses the bias resulting from such an approach when the market is imperfectly competitive. We propose a stylised two-period model of the natural gas market with no uncertainty, focusing on strategic interactions between two types of oligopolistic players—pure traders and suppliers with downstream customers—who have access to storage. We show that the true value of storage capacity is not the same for traders and for suppliers. Comparing the latter value with the traditional price-taking valuation reveals a systematic bias that tends to induce underinvestment.

1. INTRODUCTION

Some real assets—such as production plants, pipelines or storage sites—allow their owners to obtain energy on short notice under specific operational and capacity constraints. The value of these real assets is usually computed as the stream of profits that can be obtained from this asset by buying or selling the asset-related commodity in a liquid spot market, using financial tools developed for option pricing.\(^1\)

Although the recent literature has developed increasingly sophisticated methods to model the spot price process\(^2\) and to incorporate operational constraints (e.g., lead times, maximum injection or withdrawal rates and capacity constraints), it never questions two basic premises: all the relevant market information is assumed to be included in the spot price, and all the market players are assumed to take this price as given. However, these assumptions are very strong, and they are likely to be violated when operators have market power, which is the case in a number of commodity markets. Our paper

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1. Many energy companies use gas storage models developed by consultants where natural gas storage is treated as an option instrument that allows its holder to take advantage of price differentials between two periods. A parallel is drawn between these real assets and financial contracts that allow their holders to repeatedly receive variable volumes, subject to daily, monthly and/or annual constraints, at a predetermined price, thereby incorporating options known as swing or take-or-pay options (see Thompson, 1995, for a description). The pricing of these options constitutes an active domain of research (see, e.g., Jaillet et al., 2004; Barrera-Esteve et al., 2006; Carmona-Ludkovski, 2008).

2. The stochastic process governing the commodity price plays a crucial role in the pricing of related products. Models of commodity spot prices commonly use mean-reverting processes (Gibson and Schwartz, 1990; Schwartz, 1997). Models dealing with energy commodities tend to incorporate price seasonality (Manoliu and Tompaidis, 2002) and occasional price spikes (Deng, 2000).
questions the validity of conventional real asset valuation methods when both the spot market and the downstream market are imperfectly competitive, and shows that the actual value of a real asset is not the same for a pure trader and for a supplier with market power.

The assumption that the spot market is competitive, that is, that traders do not take the impact of their own transactions on the market price into account, can be questioned in industries where few traders make large transactions. In effect, market liquidity is an issue in a number of commodity spot markets, especially in the market for natural gas. Many energy markets are dominated by large suppliers, and most financial traders in spot markets are large trading companies or divisions of major banks. It is reasonable to assume that these traders are aware that their transactions affect the spot price: for instance, they will avoid flooding the market if they anticipate that the resulting price decrease will lower their profits. Martínez-de-Albéniz and Vendrell Simón (2008) show that a trader who takes the price impact of his transactions into account can refrain from arbitrage in some cases where the price spread exceeds the transaction costs, and prefers to sell less, but at a better price. Felix et al. (2009) specifically consider the impact of limited liquidity on gas storage valuation; to model the impact of traded volumes on the spot price, they introduce an illiquidity parameter that determines the bid-ask spread, but the lack of liquidity is not explicitly related to strategic interactions between firms with market power.

To illustrate the issue of real asset valuation under imperfect competition we consider the valuation of natural gas storage capacities. Because we focus on strategic interactions between firms, we abstract away from demand uncertainty. In our two-period model, demand is higher in the second period and all firms can use storage to exploit the (deterministic) seasonal spread in spot prices and obtain risk-free “arbitrage” profits. Note that although storage can be seen as an arbitrage tool allowing an operator to buy gas today and resell it at a later date, there is a fundamental difference with financial options: in a perfect market, holding a financial contract has no effect on the welfare of its owner—at equilibrium arbitrage opportunities are exhausted. However, holding a physical commodity entails costs, and capacity constraints due to storage scarcity limit the implementation of intertemporal arbitrage strategies. This explains why, even though markets are efficient, such arbitrage profits may exist in equilibrium.

3. A market is said to be liquid when trades of any size can be transacted at any moment without causing a significant movement in price. Industry players characterize market liquidity using several indicators such as the number of players active in the market, the total volume traded, the number of trades, the churn ratio (ratio of traded volume to volume delivered physically), or the bid-ask spread. The UK spot market is the most liquid natural gas market in Europe, with roughly 70 players and a high churn ratio. Conversely, the total spot trade in the most active hubs in continental Europe (Zeebrugge in Belgium, TTF in the Netherlands) is roughly a third of that on the UK hub, whereas gas demand in this region is much larger (see the ECORYS report by Rademaekers et al., 2008, based on Heren data).
4. On the APX Gas UK exchange, the five largest traders accounted for around half of traded volume in 2008 (Office of Gas and Energy Markets, 2009).
5. The model could be extended to the valuation of other real conversion assets: while storage capacity can be interpreted as converting natural gas today into natural gas at a later date, “pipeline capacity can be interpreted as an asset that can convert natural gas at one location into natural gas at a different location” (Secomandi, 2010a). Finally, the analysis could be applied to real assets that convert one commodity into another, for example, converting coal, fuel or natural gas into electricity.
6. Financial traders and the buying and selling of forward contracts or futures could also be introduced without changing the results, as long as the no-uncertainty assumption is maintained and there is free entry in the financial market.
In the case of commodities, the spot market only exists because there is a downstream market and a final demand for the commodity. Our model features two types of operators: pure traders and suppliers with downstream customers. Suppliers can use storage to earn arbitrage profits, as pure traders do, but their core business consists of purchasing gas on spot and reselling it to their customers, and storage helps them meet their customers’ needs.

Is the value of storage identical for the two types of operators? In other words, is the trading value of a real asset, based on the sole spot price, the right value for a firm with supply activities? In principle, at least in a competitive context with liquid markets, the spot price process should simply reflect the fundamentals of supply and demand; therefore it should include all the information that is relevant to any operator. Secomandi (2010a) proves that under perfect competition, the value of pipeline capacity is the same for a pure trader and a shipper. However, if there is market power in the downstream market, selling on spot or downstream ceases to be indifferent: a firm that has the ability to sell downstream (e.g., because it has the necessary authorizations, access to the network, or a large customer base) could make more profit than a pure trader with the same real asset.

To our knowledge, the only paper that compares the value of a real asset for different types of agents in an oligopolistic setting is Sioshansi (2010). Building on the analysis developed in Sioshansi et al. (2009), which describes the impact of large-scale electricity storage on electricity prices, and thus on generators’ profits and consumer surplus, Sioshansi (2010) examines the incentives for three different agent types (producers, merchant storage operators, and consumers) to use storage. Under perfect competition these incentives are identical, but in an oligopolistic setting they are lowest for producers and highest for consumers. In some respects, his model is similar to ours: all storage operators are aware that the use of storage will reduce the profits from arbitraging intertemporal price spreads, and the model compares the use of storage by operators playing different roles in the market. In Sioshansi’s model, however, demand is completely inelastic, and consumers pay the real-time spot price (there are no intermediaries between producers and consumers, which is common in the market for electricity but much less so for natural gas). Conversely, in our model, consumers buy from suppliers under two-period contracts that guarantee them a fixed price over the two periods so that demand is only inelastic in the short run. In the longer run, demand becomes elastic because suppliers compete for contracts with downstream customers, who choose the lowest price. Finally, our model emphasizes the role of initial allocation of storage capacities and proves that the results are drastically changed by whether this initial allocation is symmetric or characterized by a dominant operator.

The remainder of this paper is organized as follows. The model is presented in Section 2. Section 3 compares three methods for the valuation of new investments in storage capacity. The first is the traditional price-taking valuation. The second method computes the actual trading value of storage, taking the impact of transactions on the spot price into account. The third method computes its value for a supplier who uses it to supply his downstream customers. The analysis sheds light on the biases generated by conventional pricing techniques: while ignoring the price response to one’s transactions leads to an overestimation of the asset’s value, ignoring downstream profit opportunities leads to an underestimation. Globally, the value obtained under price-taking assumptions proves to be downward biased, except for dominant suppliers with large initial capacities: in an imperfectly competitive market, conventional methods tend to induce underinvestment.
2. The Model

The model considers the valuation of seasonal storage capacities under imperfect competition. To enhance the clarity of the analysis, we do not consider uncertainty. In the case of seasonal storage, demand for the next season is not precisely known in advance, but it can be reasonably anticipated. As for supply uncertainty, it is mitigated by the fact that we assume a continuum of small producers who can rapidly adjust their supply, so that a disruption in production or transit facilities has no significant impact on aggregate supply arriving at a hub. The model is divided into two periods, a low-demand period, followed by a high-demand period, which can be interpreted as a summer season followed by a winter season. The discount rate between the two periods is zero (alternatively, second-period prices can be interpreted as the discounted value of these prices). For any variable $y$ relating to the first period, $y'$ relates to the second period.

2.1 Assumptions

Producers sell gas in a spot market to suppliers, who resell it in a downstream market. Pure traders can also buy or sell on spot, but they have no access to the downstream market.

There is a continuum of price-taking producers with varying marginal costs, such that the aggregate production cost function is

$$ C(Q) = \frac{1}{2} Q^2 + bQ. \quad (1) $$

They produce $q$ in the first period and $q'$ in the second period. The spot price is $p$ ($p'$ in the second period). The inverse spot supply function can easily be computed: $p = b + q$ and $p' = b + q'$ in the first and the second periods, respectively.

The other firms active in the spot market are strategic players: $m$ traders (indexed by $i, i = i_1, \ldots, i_m$) and $n$ suppliers (indexed by $j, j = j_1, \ldots, j_n$) are competing in quantities. Trader $i$ and supplier $j$ are spot buyers if their spot positions $s_i, s_j, s'_i, s'_j$ in the second period are positive numbers. Suppliers sell gas to final consumers in the downstream market.

Demand for natural gas is not completely inelastic, but in practice consumer prices tend to be fixed for some period of time so that they do not respond to demand variations in the short term. In the longer term, however, contract prices can be modified. We assume that suppliers compete in quantities for two-period contracts with final consumers. Consumer demand is seasonal: a consumer signing a contract for quantity $z$ at a price $p_z$ per unit will consume a fraction $(1 - x)$ of this volume in the first period, and a fraction $x$ in the second period.

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7. Storage facilities such as depleted fields or aquifers are mainly used for seasonal storage. These specific facilities are ill-suited for short-term arbitrage because of their low withdrawal rates. This is why we rule out arbitrage operations that take place within a single season.

8. Because natural gas is largely used for heating, gas consumption is strongly influenced by weather and subject to a significant seasonal swing. In Northwestern Europe, approximately two-thirds of the gas is consumed during the winter (October-March).

9. Natural gas trading relies on three main channels: bilateral contracts, exchanges and OTC markets. An exchange is a marketplace where standardized products (commodities, derivatives or other financial instruments) are traded. Exchanges usually provide a day-ahead market, also called a spot market, and allow for trading in future (standardized) contracts. Over-the-counter (OTC) trades account for the majority of traded gas volumes, especially for forward contracts. OTC trades are neither standardized nor anonymous, and they are usually facilitated by brokers. In this article, the “spot market” relates more generally to the market where all short-term trades take place.

10. Approximately one-third of the actors in Zeebrugge, the largest European gas hub, are physical or financial traders with no downstream customers.
Real Asset Valuation under Imperfect Competition

$x$ in the second period, where $\frac{1}{2} \leq x \leq 1$. A high value of $x$ denotes a strongly seasonal demand, whereas $x$ close to $\frac{1}{2}$ denotes a flat demand profile. The demand for gas by final consumers is elastic. We use a linear inverse demand function: $p_z = d - \sum_j z_j$, where $d > b$.

Suppliers and traders have access to limited storage capacities. The use of storage between the two periods costs $c$ per unit injected. In the first period, trader $i$ and supplier $j$ inject gas into storage subject to capacity constraints (respectively, $w_i \leq K_i$ and $w_j \leq K_j$). By assumption, all inventories have to be emptied by the end of the second period. Therefore, in the second period, these quantities are withdrawn and sold either on spot, or in the downstream market.

The timing can be summarized as follows.

(1) **First period:** The producers sell $q$ at price $p$ in the spot market. Trader $i$ buys $w_i$ and injects it into inventory. Suppliers compete for contracts with downstream customers. Supplier $j$ commits to sell $z_j$ at price $p_z$ over the two periods; he buys $s_j$ on spot, sells $(1 - x)z_j$ to his customers, and saves the remaining quantity $w_j$ as inventory for the next period.

(2) **Second period:** The producers sell $q'$ at price $p'$ in the spot market. Trader $i$ withdraws $w_i$ from his stocks and sells it on spot. Supplier $j$ has to sell $xz_j$ to his downstream customers: he withdraws $w_j$ from his stocks and adjusts his spot position, so that $s_j' = xz_j - w_j$ (positive if he is a spot buyer).

To simplify the notation, the following convention is used: for any variable $y$, for $i \in \{i_1, \ldots, i_m\}$, $y_{-i} = \sum_{l \in \{i_1, \ldots, i_m\} \setminus \{i\}} y_l$, whereas for $j \in \{j_1, \ldots, j_n\}$, $y_{-j} = \sum_{l \in \{j_1, \ldots, j_n\} \setminus \{j\}} y_l$. Indices shall be dropped whenever the resulting notation is not ambiguous, e.g., $\Sigma w_i$ represents $\sum_{i \in \{i_1, \ldots, i_m\}} w_i$.

### 2.2 Equilibrium Supply and Storage

The game is solved backwards. In the second period, traders simply sell their stocks and suppliers adjust their spot market position depending on their inventories and downstream sales, so that the spot price is

$$p' = b - \Sigma w_i + \Sigma w_j + x\Sigma z_j.$$  \hspace{1cm} (2)

In the first period, competition takes place simultaneously in the downstream market and in the spot market. All traders and suppliers are necessarily spot buyers. Supplier $j$, who commits to sell $z_j$ to his customers over the two periods, simultaneously buys on spot $s_j$, sells $(1 - x)z_j$ downstream, and injects the remaining quantity $w_j = s_j - (1 - x)z_j$ into storage. The first-period spot market equilibrium is

$$p = b + \Sigma w_i + \Sigma w_j + (1 - x)\Sigma z_j.$$  \hspace{1cm} (3)

11. Durand-Viel (2007) considers a similar setting where competition between two suppliers takes place each period (e.g., each year). Two possible types of equilibria arise: either no storage is carried across the two years—which occurs when the storage cost is sufficiently high relative to final demand—or the equilibrium is asymmetric. In the latter case, one supplier carries stocks into the second year, in order to gain a leadership advantage, whereas his rival does not, but benefits from a lower spot price due to reduced demand in the spot market. The present article imposes “no stocks left in the end of the last period” as an assumption for tractability reasons, but this outcome would probably emerge as the equilibrium of a multiperiod game where the cost of storage is sufficiently high. Conversely, if cost and demand parameters correspond to the asymmetric equilibrium, the price-taking valuation would underestimate the value of storage for the leader, who overuses storage for strategic reasons.
The profit of trader $i$ is proportional to the equilibrium price spread minus the cost of storage:

$$\Pi_i = (p' - p - c)w_i.$$  \hfill (4)

As for suppliers, their activity can be decomposed into trading and supply to downstream customers:

$$\Pi_j = (p' - p - c)w_j + (p_z - (1 - x)p - xp')z_j.$$  \hfill (5)

We introduce the following definitions.\textsuperscript{12} Let

$$\alpha \equiv \frac{\partial}{\partial z_j} (p' - p - c),$$  \hfill (6)

where $\alpha$ is the marginal increase in arbitrage profits when a supplier’s downstream sales increase by one unit, which amplifies the price spread. Symmetrically, $\alpha$ is also equal to the marginal increase in supply profits when inventories increase by one unit, which reduces the price spread by exactly the same amount, thereby lowering suppliers’ purchasing costs:

$$\alpha = \frac{\partial}{\partial w_j} (p_z - (1 - x)p - xp').$$  \hfill (7)

Let

$$\beta \equiv -\frac{\partial}{\partial z_j} (p_z - (1 - x)p - xp').$$  \hfill (8)

where $\beta$ is the marginal decrease in per-unit supply profits when a supplier’s downstream sales increase: when the demand profile is not flat, more sales mean increasing the purchasing price even more in the period where it is already higher. $\alpha$ and $\beta$ are always positive, and they are larger when demand in the second period is high relative to the first period:

$$\alpha = 2x - 1,$$ \hfill (9)

$$\beta = 2(1 - x + x^2).$$ \hfill (10)

The impact of one additional unit of inventories on the profit of supplier $j$ can be expressed as

$$\frac{\partial \Pi_j}{\partial w_j} = \frac{\partial}{\partial w_j} ((p' - p - c)w_j) + \alpha z_j.$$  \hfill (11)

(1) The first term is equal to the effect of one additional unit of inventory on the profit of a pure trader holding $w_j$ in stock. This term combines two elements. The substitution effect of buying and storing one unit more in the first period instead of buying it in the second period increases profits whenever gas is cheaper in the first period. But this effect is mitigated by the impact of these transactions on the spot prices, and thus on the costs of purchasing and the revenues from selling (or the savings from

12. Note that $\alpha$ and $\beta$ are well-defined because in both equations, the right-hand side is the same for all $j$. \hfill
not purchasing) \( w_j \).

\[
\frac{\partial}{\partial w_j} ((p' - p - c) w_j) = (p' - p - c) - \left( \frac{\partial p}{\partial w_j} - \frac{\partial p'}{\partial w_j} \right) w_j \\
= (p' - p - c) - 2w_j.
\]  

(12)

(13)

(2) The second term is the global decrease in purchasing costs due to the price-smoothing effect of inventories, which makes downstream sales \( z_j \) more profitable.

For a supplier, as well as for a trader, storage is a trading tool, allowing to earn profits from the seasonal price spread. But in addition, the supplier is contractually committed to supplying to his customers in the second period where the spot price is higher; since storage helps him to meet his obligations at a lower cost, storage is more valuable for him than for a trader who lacks this obligation. As a consequence, traders can be active only if some suppliers are constrained by their storage capacity: else, the marginal valuation of storage capacity is zero for suppliers and thus negative for traders. For the same reason, at equilibrium suppliers with nonbinding storage capacities always carry more inventories than traders.

In the rest of the article, we shall focus on the case where all operators are capacity-constrained\(^\text{13}\): \( w_i = K_i \) for all \( i \) and \( w_j = K_j \) for all \( j \). The related conditions are detailed in appendix. Finally, equilibrium sales of supplier \( j \) are obtained by maximizing his profit (given by (5)) taking rival’s sales and all inventories as given:

\[
z_j = \frac{1}{(n + 1)\beta}(d - b) + \frac{\alpha}{(n + 1)\beta} \Sigma K_i + \frac{\alpha}{\beta} K_j.
\]  

(14)

### 3. Storage Valuation with Market Power

This section compares three methods for the valuation of storage capacity:

1. the price-taking valuation, \( \tilde{V} \equiv p' - p - c \),
2. the trading valuation, \( V_i \equiv \frac{\partial \Pi_i}{\partial K_i} \),
3. the supplier valuation, \( V_j \equiv \frac{\partial \Pi_j}{\partial K_j} \).

We analyze the bias related to the use of the conventional methods (that simply compute the arbitrage profits of a price-taking trader) by a trader or a supplier who enjoys market power and behaves accordingly in his day-to-day operations, typically by restricting spot or downstream sales. The price-taking valuation is identical for all operators because it is solely based on the spot price spread and does not take the specific characteristics of each operator into account. Combining equations (2) and (3) and (14) yields

\[
\tilde{V} = \frac{\alpha}{\beta} \frac{n(d - b) - \alpha \Sigma K_i}{(n + 1)} - c - \frac{3}{\beta}(\Sigma K_i + \Sigma K_j).
\]  

(15)

\(^{13}\) If this were not the case, it could be profitable for an operator with excess capacity to lend it to a capacity-constrained operator, unless withholding available capacity proved to be even more profitable. Such foreclosure strategies are not the focus of this article.
3.1 Use of Conventional Techniques by a Trader

The value of one additional unit of capacity for a constrained trader $i$ is easily obtained by reformulating equation (12):

$$V_i = \frac{\partial \Pi_i}{\partial K_i} = (p' - p - c) - \left( \frac{\partial p}{\partial K_i} - \frac{\partial p'}{\partial K_i} \right) K_i. \quad (16)$$

Note, however, that the derivative of $p$ or $p'$ with respect to storage capacity $K_i$ is not equal to its derivative with respect to inventories $w_i$: when a trader chooses $w_i$, he takes all other inventories (as well as suppliers’ sales) as given, whereas the choice of $K_i$ is made anticipating its impact on all stocks and sales.

The bias induced by the use of the price-taking valuation in the case of a trader with market power is

$$\tilde{V} - V_i = \left( \frac{\partial p}{\partial K_i} - \frac{\partial p'}{\partial K_i} \right) K_i. \quad (17)$$

The trader’s first-period purchases push the spot price upwards, whereas his second-period sales push it downwards.

$$\frac{\partial p}{\partial K_i} = 1 + \frac{n}{n+1} \frac{(1-x)\alpha}{\beta} > 0, \quad (18)$$

$$\frac{\partial p'}{\partial K_i} = -1 + \frac{n}{n+1} \frac{x\alpha}{\beta} < 0. \quad (19)$$

As a result, the price spread, and therefore the trader’s profit, is lower than if the prices were unaffected by his transactions: $\tilde{V} - V_i$ is necessarily positive. Strikingly, the number of traders $m$ has no impact on the bias, indicating that the degree of competition in the spot market does not matter. Only the size of the trader’s initial capacity determines whether his transactions will have a significant effect on spot prices. A small trader can reasonably behave as if he were a price taker.

What about the impact of imperfect competition in the downstream market? When a trader increases his storage capacity $K_i$, he lowers the price spread, and thus lower overall purchasing costs for suppliers; in return, all suppliers increase their downstream sales, which reinforces spot demand especially in the second period, thereby limiting the decrease in the price spread. This countervailing effect becomes weaker when the downstream market moves away from perfect competition, because a decrease in purchasing costs will not lead suppliers to significantly increase their sales. Accordingly, the bias is larger when the number of suppliers is small:

$$\tilde{V} - V_i = \left( 2 - \frac{n}{n+1} \frac{\alpha^2}{\beta} \right) K_i. \quad (20)$$

**Proposition 1:** A trader with market power who ignores the impact of his transactions on spot prices when computing the value of additional storage capacity always overestimates this value. This bias is reinforced by imperfect competition in the downstream market.

As a result, a trader will tend to invest “too much” as compared with the level of storage capacity that would maximize his own profit. In other words, he will generally be ready to pay too much for a given investment opportunity (as much as $\tilde{V}$ for
capacity \( K_i \) as compared with the additional profits it will yield \((V_i)\). However, the fact that the trader actually behaves in his daily operations consistently with his market power and sometimes restricts his stocks does not imply that part of the newly installed capacity will necessarily remain idle. Indeed, once investment costs are sunk, it can be optimal ex post to use the entire new capacity.

Proposition 1 does not necessarily mean that the trader’s investment will be excessive from a social welfare point of view: provided the additional capacity is actually used, the additional stocks will smooth the seasonal price spread, which will bring other traders’ profits down but will also decrease suppliers’ purchasing costs and increase total sales to downstream customers, thereby increasing consumer surplus. A detailed welfare analysis is beyond the scope of this article. Note, however, that investment is more beneficial to social welfare when it is undertaken by suppliers: the effect of stocks on the price spread (thus on trading profits) is identical whatever their owner, but downstream sales increase more with suppliers’ stocks than with traders’ stocks (see (14)).

### 3.2 Use of Conventional Techniques by a Supplier

Without loss of generality, consider the case of supplier \( j_1 \). From (5), the value of additional storage capacities for him is

\[
V_{j_1} \equiv \frac{\partial \Pi_{j_1}}{\partial K_{j_1}} = (p' - p - c) + \frac{\partial (p' - p)}{\partial K_{j_1}} K_{j_1} \\
+ \frac{\partial}{\partial K_{j_1}}((p_z - (1 - x)p - xp')z_{j_1}) = \tilde{V} - B_{1j_1} - B_{2j_1},
\]

where

\[
B_{1j_1} = \left( \frac{\partial p}{\partial K_{j_1}} - \frac{\partial p'}{\partial K_{j_1}} \right) K_{j_1}, \tag{22}
\]

\[
B_{2j_1} = -\frac{\partial}{\partial K_{j_1}}((p_z - (1 - x)p - xp')z_{j_1}). \tag{23}
\]

The error made by a supplier with market power who uses the price-taking value \( \tilde{V} \) instead of the supplier value \( V_{j_1} \) that takes into account his profits on the downstream market is

\[
B_{j_1} \equiv \tilde{V} - V_{j_1} = B_{1j_1} + B_{2j_1}. \tag{24}
\]

#### 3.2.1 First Bias: Volume Effect

The first bias \( B_{1j_1} \), always positive, is due to the fact that the use of additional storage capacities by a supplier will reduce the price spread. The intuition here is the same as in the case of a pure trader, but the suppliers’ stocks have a different impact on spot prices. Indeed, the stocks of suppliers have a larger upward impact on the spot price than the stocks of traders in the first period, but a smaller downward impact in the second period: since suppliers’ stocks stimulate downstream sales more than traders’ stocks do, they push total spot purchases upwards. Globally, the impact on the price spread is smaller when stocks are held by suppliers:

\[
B_{1j_1} = \frac{3}{\beta} K_{j_1}. \tag{25}
\]
3.2.2 Second Bias: Downstream Market Power Effect

The second bias relates to the positive effect of additional storage capacities on the downstream sales of supplier $j_1$ (see (14)). Because holding inventories allows a supplier to buy more in the first period and less in the second period, where the spot price is higher, a higher $K_{j_1}$ means lower sourcing costs, which leads him to compete more aggressively for downstream customers and increase $z_{j_1}$. Remarkably, the profit per unit supplied to downstream customers is not affected by an increase in $K_{j_1}$ (the decrease in $p_z$ resulting from sales expansion is exactly compensated for by the increase in the cost of spot purchases):

$$p_z - (1 - x)p - xp' = \frac{d - b + \alpha \Sigma K_i}{n + 1}.$$  \hspace{1cm} (26)

The resulting bias is clearly negative:

$$B_{2j_1} = -\frac{\alpha d - b + \alpha \Sigma K_i}{\beta (n + 1)}.$$  \hspace{1cm} (27)

3.2.3 Global Bias

The global bias is obtained by adding up $B_{1j_1}$ and $B_{2j_1}$, which have opposite signs:

$$B_{j_1} = \frac{3}{\beta} K_{j_1} - \frac{\alpha d - b + \alpha \Sigma K_i}{\beta (n + 1)}.$$  \hspace{1cm} (28)

$B_{1j_1}$ is proportional to the supplier’s initial storage capacity, because arbitrage profits on all units in stock are affected by the reduction in the price spread. Conversely, $B_{2j_1}$ does not depend on the initial capacity of supplier $j_1$, but its magnitude is larger when the downstream market is concentrated (small $n$). Accordingly, the sign of the global bias depends both on the degree of competition in the downstream market and on the initial allocation of storage capacities:

$$B_{j_1} < 0 \iff K_{j_1} < \frac{1}{n + 1} \frac{\alpha(d - b)}{3} + \frac{\alpha^2}{3(n + 1)} \Sigma K_i.$$  \hspace{1cm} (29)

The bias is more likely to be negative when the downstream market is concentrated and the initial capacity of supplier $j_1$ is small. In this case, he will underestimate the true value of storage, which is

$$V_{j_1} = \frac{\alpha(d - b) - \beta c}{\beta} - \frac{3}{\beta} (\Sigma K_i + \Sigma K_j + K_{j_1}).$$  \hspace{1cm} (30)

Does this mean that $j_1$ will invest less than what is optimal for him? In fact, three situations with suboptimal decisions must be distinguished. A supplier can wrongly refrain from investing ($\tilde{V} < 0$ whereas $V_{j_1} > 0$), he can invest in a situation where he should not ($\bar{V} > 0$ whereas $V_{j_1} < 0$), or he can invest when investment is desirable but his investment level is not optimal ($\tilde{V} > 0$ and $V_{j_1} > 0$, but $B_{j_1} > 0$ or $B_{j_1} < 0$).

Recall (see (15)) that $\tilde{V} > 0$ if and only if

$$\Sigma K_i < \frac{na(d - b) - (n + 1)\beta c - \alpha^2 \Sigma K_i}{3(n + 1)} - \Sigma K_i.$$  \hspace{1cm} (31)

Supplier $j_1$ wrongly refrains from investing whenever (30) is positive but (31) is not satisfied, which requires no active traders ($p' - p - c < 0$ at equilibrium). Assuming
$K_i = 0$ for all $i$, this happens if and only if
\[
K_{j_i} < \frac{\alpha(d-b) - \beta c}{3} - \frac{1}{n} \Sigma K_j < \frac{\alpha^2}{3(n+1)} \Sigma K_i + \frac{\beta c}{3n}.
\]

Accordingly, not investing can be a mistake in some situations where $K_{j_i}$ is small as compared with the average storage capacity of suppliers.

Supplier $j_1$ wrongly chooses to invest whenever (30) is negative but (31) is satisfied. This requires in particular that total storage capacity is not too small, and a necessary condition is $K_{j_1} > \frac{1}{n} \Sigma K_j$: this happens only to operators who initially own more storage capacity than the average.

**Proposition 2:** A supplier with market power who uses the price-taking valuation method, thereby ignoring both the impact of his transactions on the spot price and the downstream profits to be expected from larger stocks, underestimates the value of additional storage capacity, as long as his initial capacity is not higher than the average capacity of suppliers.

Let us focus on the third case, and consider Figure 1, excluding the upper area: from (31), $\tilde{V} > 0$ requires that $\Sigma K_j$—and therefore $K_{j_i}$—is below the upper frontier. We see that underinvestment occurs when $K_{j_i}$ is sufficiently small and $n$ is not too large (underinvestment zone where $B_{j_i} < 0$). In the corresponding numerical example, with $n = 4$ suppliers the traditional method leads to underinvestment for any supplier owning less than two thirds of total installed capacity.

In fact, if the initial capacity allocation is (at least roughly) symmetric, the bias is negative for all suppliers. In this case, conventional methods based on arbitrage pricing systematically underestimate the profits from new storage capacity and lead to underinvestment. Conversely, when one dominant supplier owns a large proportion of the available capacity, the use of conventional valuation methods can lead him to overestimate the value of additional storage capacity; however, all other suppliers will underestimate it.
To appreciate the magnitude of the bias, let us define the proportion of storage capacity owned by supplier $j_1$ as $\gamma_1 = \frac{K_{j_1}}{\sum K_i}$, and compute the relative bias

$$
\frac{B_{j_1}}{V_{j_1}} = -\frac{1}{n+1} \left( 1 + \frac{\beta c + (3 + \alpha^2) \sum K_i + (1 - \gamma_1 n) \sum K_j}{\alpha (d - b) - \beta c - 3(\sum K_i + (1 + \gamma_1) \sum K_j)} \right).$$

(33)

By assumption $V_{j_1} > 0$, so the denominator is positive. We can check that the bias is negative whenever $\gamma_1 \leq \frac{1}{n}$, but it can become positive for an operator who owns a large share of storage capacities (see Figure 2 in the case where $\gamma_1 = \frac{5}{n}$). The error resulting from the use of the price-taking valuation is significant when the market is concentrated (small $n$). When installed capacity is shared relatively evenly between all operators, the order of magnitude of the bias is a proportion $\frac{1}{n+1}$ of the actual value of the investment.

To summarize, apart from extreme cases detailed before, the use of price-taking methods generally leads suppliers with market power to underestimate the profits from storage capacity additions and, once investment costs are taken into account, to refrain from profitable investments in storage. Because suppliers with market power already tend to restrict their sales to downstream customers, this additional restriction on inventories exacerbates the welfare loss and harms consumers.

Finally, another side-effect of the use of the price-taking valuation is to inhibit the growth of small suppliers in the downstream market. In effect, if all suppliers would use the actual valuation, suppliers with less initial capacity would be more incited to invest, which would progressively re-equilibrate capacity allocation, and possibly stimulate competition. Instead, the use of the same price-taking valuation $\tilde{V}$ by all suppliers irrespective of their initial capacities tends to maintain the initial storage capacity positions of the suppliers, and hence, to freeze their downstream market shares.

4. Conclusion

This article has determined, in a simple setting, the error made by using the conventional trading valuation that ignores the market power of storage users, whether they are pure
traders or suppliers with downstream customers. The price-taking trading valuation is inadequate for a trader with market power: overlooking the volume effect of transactions on the price spread leads him to overestimate the stream of trading profits from capacity additions. Moreover, the right method for a pure trader is not necessarily well suited for a supplier. Indeed, it will be adequate only if both the upstream and downstream markets are competitive. Otherwise, ignoring downstream profit opportunities leads a supplier to underestimate the real value of storage capacity. For a supplier with an initial storage capacity no bigger than the average, the traditional method systematically underestimates the true value, and the bias amounts to approximately $1/(n + 1)$ of this value, where $n$ is the number of suppliers. Overestimation can also occur, but only in the case of a supplier owning a very large share of existing capacity.

This systematic bias leads to a real-world concern. In the case of natural gas, while an unfavorable regulatory environment is regularly blamed for the lack of new investment in underground storage facilities, this article indicates that it may not be the only reason that firms are reluctant to invest. Suppliers’ perceptions of the gains to be expected from new investments might be distorted due to the use of inappropriate valuation methods.

Why would a supplier use the price-taking valuation approach to value his storage capacities if it is biased? Why would he act optimally in daily operations, taking into account the price impact of his transactions, but not ex ante when deciding upon investments? In fact, some essentially heuristic rules can be sufficient for day-to-day trading, but misleading for decisions with a long-term impact. In a setting with uncertainty, Secomandi (2010b) proves that the profit from the optimal trading policy can be almost entirely attained simply by reoptimizing at each decision time a model that ignores uncertainty and only employs the current forward curve. However, when determining the size of a new investment in storage, modeling uncertainty is essential to take account of its extrinsic value. A parallel can be drawn with this article, which is not about uncertainty, but about imperfect competition. Traders may know how not to flood the market but are not necessarily able to model the competitive interactions in the market, which is much more informationally demanding. A major advantage of the conventional valuation techniques is that they only require an accurate forecast of spot prices. Although this might be difficult in general, in a relatively stable market, a model based on past realizations of prices and encompassing some elements related to external shocks (e.g., weather or prices of other commodities) can yield fairly good predictions of future spot prices. Much more information is required to take market fundamentals into account. In our stylized model, computing the correct valuation requires knowledge of the market structure, intensity and seasonality of final demand, storage costs and aggregate storage capacity. In a more complex setting with suppliers addressing different categories of customers, detailed data about the different demand segments might be needed, as well as storage capacities and costs of all market players. This information is difficult to collect and is sometimes not publicly available. As a consequence, the choice of conventional techniques can be explained by an insufficient knowledge of demand and of the functioning of the market. As all market players become more experienced and this sort of information proves to be relevant for making the right choices, new valuation techniques should be developed that more explicitly take strategic interactions into account.
Appendix: Conditions for Storage Capacities to be Binding

If all the other traders and suppliers are capacity-constrained, the best response of trader $i$ to other operators’ stocks and to suppliers’ sales is

$$w_i = \frac{1}{4}(\alpha \Sigma z_j - c) - \frac{1}{2}(\Sigma K_j + K_{-i})$$  \hspace{1cm} (A1)

if the right-hand side is positive and lower than $K_i$, else $w_i = 0$ or $w_i = K_i$. Because supplier $j$’s sales are given by (14), if trader $i$ is not capacity-constrained, his equilibrium inventories are

$$w_i = \frac{1}{4\beta - \alpha^2} \left( \frac{n}{n+1} \alpha(d - b) - \beta c - 3(\Sigma K_j + K_{-i}) - \frac{\alpha^2}{n+1} K_{-i} \right)$$  \hspace{1cm} (A2)

provided that these inventories are positive, which is true if and only if

$$\frac{n}{n+1} \alpha(d - b) - \beta c > 3(\Sigma K_j + K_{-i}) + \frac{\alpha^2}{n+1} K_{-i}. \hspace{1cm} (A3)$$

Trader $i$ is capacity-constrained if $K_i$ is lower than the right-hand side of (A2).

Similarly, if all the other suppliers and traders are capacity-constrained, the best response of supplier $j$ to their stocks is

$$w_j = \frac{1}{4}(\alpha(z_j + 2z_{-j}) - c) - \frac{1}{2}(\Sigma K_i + K_{-j})$$  \hspace{1cm} (A4)

if the right hand-side is positive and lower than $K_j$, else $w_j = 0$ or $w_j = K_j$. Because supplier $j$’s sales are given by (14), if he is not capacity-constrained, his equilibrium inventories are

$$w_j = \frac{1}{4\beta - \alpha^2} \times \left( \frac{2n-1}{n+1} \alpha(d - b) - \beta c - 2(\beta - \alpha^2)(\Sigma K_i + K_{-j}) - \frac{3\alpha^2}{n+1} \Sigma K_i \right).$$  \hspace{1cm} (A5)

provided that these inventories are positive, which is true if and only if

$$\frac{2n-1}{n+1} \alpha(d - b) - \beta c > 2(\beta - \alpha^2)(\Sigma K_i + K_{-j}) + \frac{3\alpha^2}{n+1} \Sigma K_i. \hspace{1cm} (A6)$$

Supplier $j$ is capacity-constrained if $K_j$ is lower than the right-hand side of (A5).

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