

Cahiers du LASER

n°24-09-08

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September 26, 2008

Abstract

In this paper, we study how competition on downstream gas markets is influenced by sourcing decisions in the supply chain. We analyze the sequential relationships between storage decisions and intermediate pricing in spot markets. We show that an upstream leadership in the access to storage facilities leads a dominant firm to adopt strategic storage decision. This strategy consists in stockpiling more than supplied in the downstream market. This behavior is a part of a raising rival's cost strategy for the leader. Furthermore in some cases, optimal regulation of gas storage access may not prevent such a behavior.

JEL Codes: L10, L50, Q40.

Key words: Storage, spot market, gas markets, regulation.

1 Introduction

Faced with the predicted increase in gas needs in the European Union¹ within a context of gas market opening, authorities in Brussels underline the need for developing gas sourcing

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¹Retail energy market opening in Europe, cost reduction in electricity generation from gas, abundant gas resources available world-wide, contribute to explain natural gas expansion in Europe as well as its central role in European energy supply for next decade.

arrangements other than long-term contracts. Gas availability must be ensured over a shorter time scale in order to allow an actual “gas-gas” competition in the market². The report published by the Commission of European Communities (2007) underlines the lack of liquidity of European gas markets.³ In this context, developing spot markets, gas hubs and third party access to storage capacities could increase the supply liquidity and enable operators to discriminate between their gas supply sources in a shorter term. Due to this flexibility, gas firms will be encouraged to implement an effective asset management for their supplies and discriminate between available sources in the short and long term.⁴

Supply source diversification is a flexibility tool for gas firms, particularly during peak demand periods and when resources are insufficient with respect to the subscribed long term contracts. In broad, a gas producer can manage its supply portfolio by using several flexibility tools: Subscribing long term contracts, upstream vertical integration⁵, or even using spot markets for obtaining the quantities which are not covered by the internal supply sources and long term contracts. Lastly, the operator can use storage capacities to satisfy the demand increase during peak periods. Following the European Union’s decision, storage capacities have been transferred to third parties since August 2004 (third party access to storage). In this context, it is obvious that storage will become a significant flexibility tool when choosing a gas supply portfolio as it is observed in many American states . This should enable gas operators, who are already in the market, to use another short term adjustment tool in addition to the spot market.⁶

As specified in the Eurostat report (2004) “Free gas [in Europe] (gas available on short and medium term basis excluded long term contracts) represents only 25 Gm³ compared with the consumption representing 435 Gm³ a year.” In this context, storage is an additional adjustment tool which may even replace the spot market as regards satisfying the demand during peak periods.⁷ In this region, in particular due to limited storage capacities, trading-off between storage and spot market is not usual in the European Union. Traditionally, storage is considered as a tool enabling to optimize the gas transmission system and to ensure continuity of the service. In our framework, storage not only has

²For an economic analysis of competition in gas market see Cremer, Laffont (2002).

³There is "sub-optimal levels of liquidity in these [european] markets. In particular, the prevalence of long-term supply contracts between gas producers and incumbent importers makes it very difficult for new entrants to access gas on the upstream markets.", DG Competition Report on Energy Sector Inquiry, 10 January 2007, p. 8.

⁴For instance in France, long term contracts represent 80% of supply sources for Gaz de France. In the same way, long term contracts represent 90% of supply sources for the Belgian incumbent Distrigas (annual report for 2005).

⁵For instance, this has been done by merger and acquisition of holdings in oil and gas companies.

⁶Since 1998 in Europe, gas hubs have been established. For example, these spots markets are located in Bacton (UK), Zeebrugge (NL) and Emdem (Germany).

⁷These peak periods are strongly correlated with the winter season.

this public service dimension, but can also be used for influencing the strategic decisions made by competitors. This strategic dimension is reinforced by the fact that, in this case, storage concerns an intermediate good and can therefore influence vertical relationships between oil-gas operators and suppliers through the spot market. The main topic of this paper is the study of storage behaviors as a means for raising rivals' costs.

Economic literature on storage activities is relatively extensive. Traditionally, storage is considered as an investment enabling firms to adjust their supply when demand is uncertain or exposed to cyclical fluctuations. Three main motivations are identified in economic literature for explaining the benefits of storage for firms: speculation, precaution and seasonal production smoothing. The storage speculative function is relatively well accepted. In this case, storage enables firms to obtain a positive income faced with an exogenous shock which, for instance, influences the market price of the stored good. The precautionary motive is a regulatory function; the stock allows firms to regulate market supply in answer to an uncertain demand when their production capacity is not very elastic. More precisely concerning gas storage, Chaton et al. (2006) analyze optimal depletion of gas reserves in various scenarios, and particularly the opportunity for regulatory authorities to maintain safety stocks. Lastly, firms may choose storage in order to smooth the cyclical fluctuations of the demand. In addition to these traditional functions, storage is a major subject in literature about oligopolistic competition within a dynamic context. Thus, for instance, Kirman and Sobel (1974), Philips and Richard (1989) study storage in a context of intertemporal price discrimination. In this case, storage introduces an intertemporal fixed price reliance in as much that decisions made during a certain period are dependent on actions from previous periods. The strategic function⁸ of storage has initially been analyzed by Arvan (1985), Saloner (1987) and Pal (1991, 1996). Storage ensures a strategic function if it influences the future decisions of rival firms. It is due to the fact that it may be used by firms as a commitment means based on quantities. An oligopolistic firm may be induced to invest in storage capacities to preempt the future production of its competitors. In line with this perspective, Saloner (1987) and Pal (1991, 1996) consider a duopoly model in which, during the first period, firms choose their advance production (which is assimilated to their storage level) and then, over a second period, sell their products in the market. With a Stackelberg leadership, they show firms may be induced to produce in advance even if their production is more expensive during the first period. Poddar and Sasaki (2002) examine incentives for firms to produce in advance in a multiperiod competitive setting. They show that advance production can be a strategy to create endogeneously a Stackelberg leadership. Storage might be a tool to implement such a strategy.

⁸Baranes et al. (2005) also consider that storage facilities can be strategically used as a foreclosure tool.

From an empirical point of view, a recent academic literature focuses on the links between storage decisions and natural gas prices. In these papers (see for example Modjtahedia and Movassagh, 2005 and Xiaoyi, 2007), it is underlined that storage have impact on the volatility and level of natural gas prices. An other very interesting paper Egging and Gabriel (2006) study the impact of storage capacities on market power in the European gas market. In this way, our model integrates a relationship between the storage decision and the intermediate price within the spot market. In our paper, the dynamics of the spot market integrate externalities related to strategic storage decisions; this contributes to increase the gap between the spot market gas price and the corresponding marginal cost. We show that an upstream leadership in the access to storage facilities leads the dominant firm to adopt a strategic storage decision. This strategy consists in stockpiling more than supplied in the downstream market. This behavior is a part of a raising rival's cost strategy for the leader. Furthermore, one can think that optimal regulation of the access to storage facility would prevent such a behavior. However especially when storage activity is not too costly, we show that it is not the case since strategic storage helps reducing the spot market price.

Our paper is organized as follows. In section 2, we develop the framework of the model. In section 3, we consider the benchmark case of the game where gas suppliers are symmetric operators. In section 4, we assume that one particular gas operator is a leader for its storage strategy. For these two sections, a welfare analysis of game equilibria will be carried out in order to compare the social impacts for all the strategic behaviors of the firms. The last section will include our conclusions.

2 Model

We consider an industry in which n operators are competing in the market of a homogeneous good, i.e. natural gas. Consumption behaviors are represented by the gas demand addressed to n downstream firms or retailers. The gas demand is denoted $p(Q)$ it depends on Q the aggregated volume of gas traded in the market. The downstream supply of gas for a firm i is noted q_i . In order to provide this supply, the gas supplier uses the volume injected in a storage facility denoted y_i . Two cases may be encountered. In the first case, the quantity of stored gas, y_i , is insufficient for supplying the quantity of downstream gas, q_i . In this situation, the gas supplier may use the spot market for buying additional quantities, z_i , in order to satisfy the demand. In the second case, the quantity of stored gas exceeds the demand. The gas producer may then sell his excess quantities in the spot market.

Therefore, for each gas operator, there is a relationship between his supply in the final

market, the quantity of gas injected in the stock and the position in the spot market, which is as follows:

$$q_i \leq z_i + y_i. \quad (1)$$

This relationship represents adjustment possibilities (stock versus spot) available to gas downstream suppliers for satisfying the downstream market. Lastly, s denotes the spot price of gas, which therefore depends on buying or selling operations carried out by gas suppliers and traders in this market. We consider that these $n \geq 2$ operators competing downstream in the final market obtain their gas supply upstream through long term contracts (or through internal supplies) at a constant marginal price $\gamma \geq 0$. As underlined above, we wish to focus on supply trade-offs in the short term and understand our results in terms of adjustment strategies. In this context, the supply taken into consideration is intended for storage purposes enabling operators to satisfy the demand during peak periods in a locally-defined market. Gas firms may use a spot market or storage capacities. This enables them to complete their supply portfolio when storage conditions are not attractive with respect to the spot market price, or when the storage is insufficient for satisfying the demand expressed downstream. In this paper, storage and spot are considered as two supply processes which are substitutes or complementary.

In the spot market, m traders compete with gas firms. The net supply of a trader⁹ indexed by j is denoted w_j . A trader has a seller position when $w_j > 0$ and a buyer position whenever $w_j < 0$. We consider that these traders buy gas in similar cost conditions as gas firms. This simplifying assumption enables us to focus on the impacts generated by the spot market on local downstream competition between gas suppliers.

We assume further that gas operators as well as traders aim to maximize their profit. The profit made by gas suppliers is given by the difference between returns made in the downstream market and the total cost. The storage access cost is ay_i and the cost in the spot market is given by $s z_i$. Profit for firm i is then:

$$\Pi_i(q_i, q_{-i}, y_i, y_{-i}) = p(Q) q_i - (a + \gamma) y_i - s z_i \quad (2)$$

This expression accounts for the two situations described above: the situation in which the gas supplier uses the spot market to complete his supplies (in this case he bears cost $s z_i > 0$), and the situation in which he uses his additional stored gas and sells it in the spot market (in this case he benefits from returns $-s z_i > 0$). Binding¹⁰ (1) and substituting z_i ,

⁹Actually, pure traders don't exist in gas hubs. In general, they are operators trading on parallel local markets. Here the assumption is made that these firms are operating on the spot market as arbitragers taking advantage of pricing of the energy resource. Nowadays, on gas spot markets gaz in Austria, Netherlands, Belgium or UK, many actors buy or sell gas whereas they are completely disconnected from end-users.

¹⁰For all decision pair (q, y) , one can see that choosing z_i (net position on spot market) obeys to the

the profit of gas suppliers (2) is:

$$\Pi_i(q_i, q_{-i}, y_i, y_{-i}) = (p(Q) - s)q_i - (a + \gamma - s)y_i$$

The profit for traders j (with $j = 1, \dots, m$) is given by

$$\pi_j(w_j, w_{-j}) = (s - \gamma)w_j.$$

Two cases may again occur. A situation in which the trader sells gas ($w_j > 0$) in the spot market when $s > \gamma$, and a situation where he buys gas ($w_j < 0$) when his supply cost γ is greater than the spot market price ($s < \gamma$). In order to neutralize the impacts generated by the nature of supplies, without loss of generality, γ is normalized to zero.

Lastly, the storage activity is assumed to yield a profit for the storage firm equals to $\Pi_s = (a - c) \sum_{i=1}^{i=n} y_i$, where $a > 0$ is the uniform price or storage access charge¹¹ and $c > 0$ is the unit and marginal cost of the activity.¹²

We consider a three-stage game which is analyzed in the following sections. The timing of this game is as follows. In the first stage, gas suppliers determine their storage strategy (i.e. they choose y_i). In the second stage, operators (gas suppliers and traders) determine which purchases and sales are to be performed in the spot market (choosing w_j and z_i). In the third stage, gas retailers compete in the downstream gas market (choosing q_i). This game is solved by backward induction for two distinct settings. A first configuration where firms (at each stage) are symmetric and a second one where a firm has leadership in the access to the storage facility.

3 Storage, spot market and competitive gas supply

In this section, we consider the sequential game described so far considering that firms (at each stage) are symmetric. This constitutes our benchmark competitive configuration.

following first-order conditions (where $\lambda \geq 0$ is the multiplier) for all i

$$\begin{cases} \frac{\partial \Pi_i(q_i, q_{-i}, y_i, y_{-i})}{\partial z_i} + \lambda = 0 \\ \lambda(y_i + z_i - q_i) = 0 \end{cases} \Leftrightarrow \begin{cases} -s + \lambda = 0 \\ \lambda(y_i + z_i - q_i) = 0 \end{cases} \Leftrightarrow s(y_i + z_i - q_i) = 0.$$

Then without loss of generality (except when $s = 0$), it must be the case that $z_i = q_i - y_i$. However, we here consider implicitly that the balance between stored and sold quantities is never zero. Indeed we focus on impacts of storage decisions onto the endogenous spot price and thereby on the trade-off between stock and spot for the downstream market supply.

¹¹At this stage this price is exogenous, but we will consider afterwards scenarios for which this access charge is either regulated by a social planner or determined by the storage operator himself.

¹²To simplify, we assume constant return to scale in the storage activity but removing this assumption, for instance by adding a fixed cost, doesn't weaken our results.

Solving by backward induction, we first consider competition in the downstream market, then in the spot market and finally at the storage level. Finally, we look at the optimal welfare regulation of the storage access charge.

3.1 Competition

• **Competition in the downstream market.** We assume that the n gas suppliers are competing à la Cournot. We assume that the final gas demand is linear and expressed by $p(Q) = 1 - Q$. At the downstream competitive equilibrium, the profit of a gas supplier i , is maximized if he chooses q_i^* such as $\Pi_i(q_i^*, q_{-i}^*) \geq \Pi_i(q_i, q_{-i}^*), \forall q_i \geq 0$. In this case, we can easily explicitly obtain the Cournot equilibrium, for any value of i :

$$q_i^* = q^*(s, n) = \frac{1 - s}{1 + n}. \quad (3)$$

Consequently, the market price is written as $p^*(s, n) = \frac{1 + ns}{1 + n}$. In order to ensure that equilibrium values are not negative, i.e. $q^*(s, n) \geq 0$ and $p^*(s, n) \geq 0$, the spot market price must be within the following range :

$$-\frac{1}{n} \leq s \leq 1. \quad (4)$$

• **Competition in the spot market.** In this framework, the spot market allows gas suppliers some flexibility in their sourcing strategy. According to their position in storage y_i , firms trade quantities $z_i = q_i - y_i$ in the spot market while traders adopt w_j as a position. Therefore, the spot market is organized as follows. On one hand, the overall net demand in the spot market is the sum of the downstream total supply ($Q^*(n, s) = \sum_{i=1}^{i=n} q_i^*$) and all storage decisions ($Y = \sum_{i=1}^{i=n} y_i$). On the other hand, the overall net supply of traders is expressed as $\Omega = \sum_{j=1}^{j=m} w_j$. Thus price s involves the equilibrium in this market as follows:

$$\sum_{i=1}^{i=n} (q_i^* - y_i) = \sum_{j=1}^{j=m} w_j \Leftrightarrow nq^*(s, n) = Y + \Omega.$$

Using (3), the inverse demand in the spot market is:

$$S(\Omega + Y) = 1 - \frac{n + 1}{n} (Y + \Omega). \quad (5)$$

We assume that competition in the spot market yield traders to adjust their position so as to maximize their profit, which is expressed as $\Pi_j(w_j, w_{-j}) = S(\Omega + Y) w_j$. The Nash-Cournot symmetric equilibrium between traders corresponds to the net supply

$$w(Y, n, m) = \frac{n - Y(n + 1)}{(n + 1)(m + 1)}. \quad (6)$$

The equilibrium supply of a trader therefore decreases according to the quantities stored by all gas suppliers (represented by Y), but this effect decreases according to the degree of competition in the spot market, as m decreases. Besides, this equilibrium supply increases according to the degree of competition in the downstream market (when n increases).

From (5) and (6), we deduce the equilibrium price of the spot market:

$$S^*(Y) = \frac{n - (n+1)Y}{(1+m)n}. \quad (7)$$

From this expression, we observe that the spot market price is all the more high as stored quantities are low. This result is not surprising considering that storage is an adjustment process which can be used as a substitute for the spot market. Storing a greater quantity of gas leads reducing the demand in the spot market; this results in a decrease of the spot market price, all other things being equal. Thus, at this stage of the game, downstream supply decisions (as well as the price in the final market) can be expressed as a function of the overall storage decision $Y = \sum_{i=1}^{i=n} y_i$:

$$q_i^*(Y) = q^*(S^*(Y), n) = \frac{(n+1)Y + mn}{n(m+1)(n+1)} \quad (8)$$

It may be noted that the supply in the final market increases according to the storage level decreases when the storage quantity increases.

• **Storage decisions.** In the first stage, gas suppliers choose the quantity of gas they want to store at cost a so as to be able to sell it in the downstream market or in the spot market. The profit of a gas supplier is:

$$\Pi_i(y_i, y_{-i}) = [p(nq^*(S^*(Y), n)) - S^*(Y)]q^*(S^*(Y), n) - (a - S^*(Y))y_i$$

where $Y = y_i + Y_{-i}$ and $Y_{-i} = \sum_{j \neq i} y_j$.

The best reply function $y_i(Y_{-i})$ of gas producer i is implicitly given by (using envelope theorem):

$$(n-1)p'(\cdot)q^* \frac{dq^*}{ds} S^{*'}(Y) - (q^* - y_i) S^{*'}(Y) = a - S^* \quad (9)$$

From (9), we can identify the various effects of any variation of stored quantities y_i on the profit of a gas producer: a final market effect, a spot effect and a cost effect. The first term, $(n-1)p'(\cdot)q^* \frac{dq^*}{ds} S^{*'}(Y)$, is clearly negative and measures the final market effect. An increase of stored quantities produces a negative impact on the profit earned in the final market. Indeed an increase of stored quantities yields a decrease in the spot price which helps reducing the sourcing cost ($S^{*'}(Y) < 0$ as can be seen from 7). In turns, this increases the rivals' total supply in the final market $(n-1) \frac{dq^*}{ds} S^{*'}(Y)$ and thus decreasing the final price. Summing up, the downstream profit decreases when stored quantities increase since $-\frac{n-1}{(1+m)n} q^* < 0$.

The second term, $-(q^* - y_i) S'(Y)$, represents the *spot effect*. Hence, increasing stored quantities results in a decrease in the spot price. This directly leads to decreasing the sourcing cost for quantities bought in the spot market or decreasing the receipts if the gas supplier sold his volumes in excess on the spot market, whenever $y_i - q_i^* > 0$.

The last term, $a - S^*$, represents the *cost effect*, more precisely the effect on the net cost of storage injection. Here, an increase in stored quantities increase leads to an increase of the relative supply cost if $S^* < a$ (respectively, a decrease if $S^* > a$).

Combining (7), (8) and (9), we can determine the stored quantities for each gas supplier¹³ $y^*(a, n, m)$ as well as equilibrium levels of trade in the spot market $w^*(a, n, m)$ and price $s^*(a, n, m)$.

As a result using (3), $q^*(a, n, m) = q^*(s^*(a, n, m), n)$ is the downstream equilibrium level for the gas supply. Notice that it exists an access charge level a_n such that $y^*(a_n, n, m) = 0$, hence if $a > a_n$ gas sourcing is exclusively done from the spot market.

From now, we define *strategic storage* as a situation in which the quantity of gas offered in the downstream market by a distributor firm is lower than the quantity of stored gas (that is $q^*(a, n, m) - y^*(a, n, m) < 0$). We can show¹⁴ the following result.

Proposition 1 *At the symmetric equilibrium, no strategic storage occurs, retailers always store a quantity of gas which is lower than their supply in the downstream market. As a result the spot price includes a mark-up i.e. $s^* > 0$.*

This result means that gas suppliers store insufficient quantities of gas compared to their supply in the final market. Indeed at the equilibrium, to adjust their sourcing operations they may use both spot market and storage capacities as flexibility tools. However, it is necessary for gas suppliers to use the spot market in order to complete their gas sourcing. It should be noted that even though access price is very low¹⁵ i.e. $a < a^*$, the equilibrium strategy employed by gas suppliers is not an exclusive adjustment of their sourcing from the gas storage. This result may firstly appear surprising, because the spot market price is greater than the access price: when a varies, the spot price increases less rapidly than access price (a) due to the fact that the number of operators in the spot market is higher ($n + m$) than the number of operators having access to storage (n). However, this result is based on a rather simple intuition: if gas suppliers choose to use storage only, then the demand becomes equal to zero in the spot market and the spot price is also equal to zero. Therefore, deviating using spot adjustments becomes advantageous for all producers. The equilibrium defined in proposition 1 thus represents

¹³Their expression can be found in the proof of proposition 1.

¹⁴All proofs are given in appendix.

¹⁵Where a^* is such as $s^*(a^*, n, m) = a^*$.

how gas suppliers adjust between both sources. This argumentation is identical when $a > a^*$.

3.2 Welfare regulation

Social welfare is defined as the sum of the consumers' surplus and profits of gas suppliers, traders and the owner of the storage facility. At the equilibrium depicted in the previous subsection, it writes:

$$W^n(a, c, n, m) = \int_0^{nq^*(\cdot)} p(Q) dQ - nq^*(\cdot)p(nq^*(\cdot)) + n\Pi(\mathbf{q}^*, \mathbf{y}^*) + m\pi(\mathbf{w}^*) + \Pi_s$$

Now, we examine the optimal policy for the regulation of the access charge. Denoting a_w^n the optimal access charge, we can state the following result.

Proposition 2 *It may be socially optimal to avoid a gas sourcing exclusively from storage facilities even if access charge is low ($a_w^n \leq a_n$) whenever $c \in [\underline{c}^n, \bar{c}^n]$. This policy is less likely when the spot market becomes more competitive ($\frac{d(\bar{c}^n - \underline{c}^n)}{dm} < 0$).*

More precisely if $c \in [\underline{c}^n, \bar{c}^n]$, welfare is maximal when the access charge level a_w^n is such that the sourcing strategy consists in using a mix of both spot and storage (whenever $a_w^n < a_n$). In this case, for small values of the access charge, it is socially preferable to avoid an exclusive sourcing from the stockpile even though it is relatively less expensive. Besides, when the spot market is not very liquid (i.e. m is low), the spot price increases, and all other things being equal consequently, the spot market is less interesting. This explains the extension of the range where mixed sourcing is socially optimal. It should also be noted that in this intermediate area of the storage cost, there exists a subinterval $[\underline{c}^s, \bar{c}^n]$ where $\underline{c}^s > \underline{c}^n$, in which the optimal regulation of the access charge ($a = a_w^n$) also entails positive profits for the storage operator. As a result, regulating the access charge at price a_w^n is sustainable for the storage firm if storage costs are not too low.

4 Leadership in the access to storage

Now we consider that one firm among the n gas suppliers is a leader when he chooses its storage strategy. This implies that the leader has a favored access to storage compared to other gas suppliers hereafter referred to as “the fringe”. In the following, we will note

the leader as l and a gas firm representing the oligopolistic “fringe”¹⁶ as f . Leadership for storage access has no effect on the structure of competition in the final market, nor on the structure of the spot market. Consequently, stages 2 and 3 of the game remain unchanged (refer to section 3), and only the initial stage (storage stage) has to be reconsidered.

4.1 Effects of Stackelberg leadership on storage decisions

The storage stage is now a sequential subgame where followers take the leader’s storage decision y_l as given. The followers have the same best reply function as in the competitive case (defined by 9) except that it is based on the symmetric equilibrium within the fringe. The best reply function for a fringe firm can be expressed as a function of the only storage decision made by the leader because $Y_{-i} = y_l + \sum_{j \neq i, j \neq l} y_j$.

After some tedious calculus¹⁷, we obtain the interior equilibrium storage strategies for the leader and the followers:

$$\hat{y}_l(a, n, m) = \frac{B(n, m) - A(n, m)a}{2(n+1)^2(n^2(n+1)(m+1) - 2(n-1))}$$

$$\hat{y}_f(a, n, m) = \frac{D(n, m) - C(n, m)a}{2(n+1)^2(n^2(n+1)(m+1) - 2(n-1))}$$

with $A(n, m) > 0$, $B(n, m) > 0$, $C(n, m) > 0$ and $D(n, m) > 0$.

The last expressions show how leadership affects the stockpile-spot mixed adjustment. When determining his gas supply, the leader only uses the storage for lower access charge values. On the one hand, the impact of leadership induces a reduction in the storage adjustment for fringe firms for relatively low access charge levels, i.e. $a < a^*$. On the other hand, as soon as the storage becomes rather expensive (i.e. $a > a^*$), the presence of a leader leads fringe firms to inject more than without leadership. As a result, for small storage access charge values, the leader takes advantage of increasing the stored quantity which is not very expensive (when $a < a^*$). In this case, the fringe is then driven to buy more gas from the spot market.

Let $\hat{a} < a^*$ such that $\hat{y}_l(\hat{a}, n, m) = q^*(\hat{s}(\hat{a}, n, m), n)$ where $\hat{s}(a, n, m)$ is the equilibrium spot price.

Proposition 3 *For low access charge ($a < \hat{a}$), the leader raises its rivals’ cost using strategic storage.*

¹⁶We adopt an oligopolistic fringe assumption whereas perfectly competitive because of the leader on the access to storage cannot reasonably leads to consider the other gas firms to be atomistic on the downstream market.

¹⁷They are given in appendix, proof of proposition 3.

This Proposition 3 can be illustrated in the following figure:

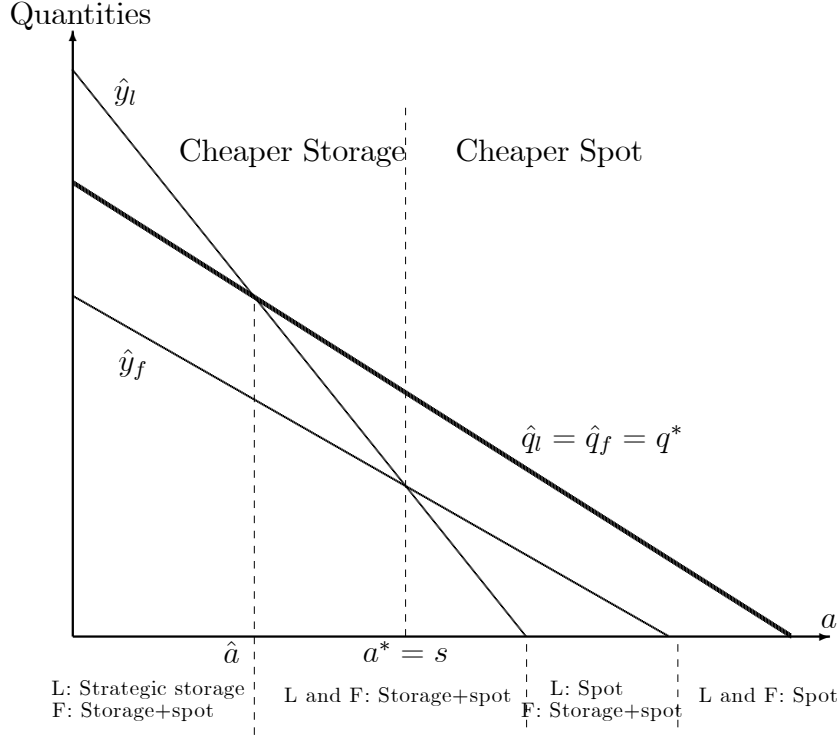


Figure 1: “Strategic storage” (L: leader, F: followers/fringe)

For relatively small storage access charge ($a < \hat{a}$), the leader should decide to store significant volumes. In this case, fringe firms react by buying part of their sourcing operations in the spot market, which is relatively more expensive at the equilibrium. Similarly, when the storage access price increases ($a > \hat{a}$), the leader reduces his stored quantities and he even interrupts storing activities and only uses the spot market for very high values of a . This induces fringe firms to react using a relatively more expensive storage strategy.

From the leader point of view, this behavior can be as a part of a “raising rivals’ cost” strategy¹⁸. For relatively low access charge levels ($a < \hat{a}$), the result is immediate since the residual storage capacity left to the fringe is consequently reduced. When the access charge is higher ($a > \hat{a}$), this effect remains unchanged but in a less intuitive manner. If storage capacities are restricted¹⁹, the fringe would prefer to supply smaller volumes in the downstream market rather than using the spot market in order to satisfy the demand. This can be explained by the strategic position of the leader in the spot market: using the spot market would be too costly for the fringe firms.

¹⁸As defined by Salop and Scheffman (1983).

¹⁹Notice that when storage facilities are capacity constrained (as it is actually expected), the strategic storage behavior is all the more harmful for fringe firms.

Although this type of strategy may seem very profitable for the dominant firm, it may have a negative impact at a social level: decrease in the profits of other firms (fringe, storage owner, traders) and in the consumers' surplus. It then appears necessary to study the welfare impacts when this type of strategy is applied.

4.2 Welfare regulation with leadership

In this leadership situation, social welfare writes now:

$$W^s(a, c, n, m) = \int_0^{n\hat{q}(\cdot)} p(Q) dQ - (n\hat{q}(a, n, m)) p(n\hat{q}(a, n, m)) + \\ + \Pi_l(\hat{y}_l) + (n-1) \Pi(\hat{\mathbf{q}}, \hat{y}_l, \hat{y}_f) + m\Pi(\hat{\mathbf{w}}) + \Pi_s$$

In order to estimate the impact of strategic storage on the social welfare, we analyze the optimal regulation of the access charge. Now, we solve the related problem $\max_{a \geq 0} W^s(a, c, n, m)$. We denote a_w^s the optimal access charge with leadership. Whenever the optimal access charge lies in the range where strategic storage represents an optimal strategy for the leader, this would mean that the regulator prefer this kind of strategy in terms of welfare. Thus in the following result we compare a_w^s and \hat{a} .

Proposition 4 *Strategic storage decision by the leader may be socially optimal for a low value of the storage cost ($c < \tilde{c}$). Moreover, this policy is more likely when the spot market becomes more concentrated such as $\frac{\partial \tilde{c}}{\partial m} < 0$.*

For relatively low storage cost values, the socially optimal access charge a_w^s is lower than \hat{a} , i.e. the value below which the leader chooses a strategic storage behavior. In this case, it is socially preferable to let the leader preempt capacities in the storage facility. On the one hand, stored quantities in excess are sold by the leader in the spot market and contribute to decreasing the spot price (indeed $s^* > \hat{s}$); this is considered as a Pareto improving change. On the other hand, when the storage cost increases, it is preferable for the regulator to avoid this "overstoring" practice.

It should be noted that the value of \tilde{c} (for which $a_w^s = \hat{a}$) depends on the number m of traders active in the spot market. In other words, when the spot market is concentrating (m decreases), the size of the range for which strategic storage is socially preferred increases. As a result, when spot markets are not very liquid (that is the case in the European Union), an optimal strategy for the regulator may consist in allowing operators to strategically manage the storage. This type of strategy is a way of increasing the quantities of gas available in the markets in order to reduce the price of gas resources.

5 Conclusion

In this paper, our analysis concerns gas supply flexibility in a competitive context, which is the European situation anticipated over the next ten years. Two flexibility tools can be employed by gas firms for choosing their sourcing portfolio: the spot market and the storage capacities assumed open to competition (Third Party Access to Storage). The described model enables us to identify a classical industrial organization in the gas sector: a final market completed with “flexibility” markets: spot and storage. These markets are operating for two periods of time. In a first period (off peak period, “summer”), an initial strategic choice is made concerning the stored quantities to be used to satisfy part of the demand during peak periods. In a second period (peak period, “winter”), two decisions are taken sequentially: the gas producer firstly determines the quantities which are bought or sold in the spot market; he then serves the downstream peak demand. After having calculated the equilibria of the various markets, an analysis in terms of general welfare is conducted in order to examine possible optimal regulation decisions (in particular, optimal regulation of the storage access charge).

In relation to this paper, we have presented two types of results. On the one hand, sourcing diversification is a profitable strategy for gas suppliers even when the spot price of gas is higher than the storage access cost.²⁰ This "stockpile vs spot" mixed adjustment is all the more preferable from a social point view as the spot market is not very liquid, i.e. relatively concentrated. On the other hand, in the case of storage decision making leadership, the leader uses storage in a strategic manner for increasing the cost of his competitors. This speculation-based storage strategy may be socially efficient, particularly when the spot market is not very liquid (low number of traders). Thus, when the storage activity cost is not too high, it may be preferable for regulatory authorities to determine an access charge for which the leader chooses a strategic storage decision. In this case, excess stored quantities are sold by the leader in the spot market; they enable to increase supply liquidity, and thus, to reduce the gas price at a downstream level in the chain. By enabling a leadership rent, the storage access charge becomes a tool which can be used by the regulator for increasing the gas resource in the spot market.

Appendices

• **Proof of Proposition 1.** In order to prove this Proposition, we first solve the second and first stages of our game respectively. The last stage equilibrium is trivial, see (3). *Second stage.* From (5) and taking Y as given, trader’s profits write as $\mu_j(w_j, w_{-j}) =$

²⁰In our paper, this profitable diversification is not linked to the typical risk management strategy.

$S\left(w_j + \sum_{h \neq j} w_h + Y\right) w_j$. Maximizing $\pi_j(w_j, w_{-j})$ with respect to w_j for all j yields the first-order condition:

$$1 - 2\frac{n+1}{n}w_j - \frac{n+1}{n}\left(Y + \sum_h w_h\right) = 0.$$

It is sufficient since the profit function is concave in w_j :

$$\frac{\partial^2 \pi_j(w)}{\partial w_j^2} = -2\frac{1+n}{n} < 0.$$

Solving for w when $w_j = w_h = w$, leads to the Nash-Cournot symmetric equilibrium on the spot market (6).

First stage. Substituting (6) in (5) leads to (7). However for the downstream equilibrium to exist, (4) must be verified:

$$S^*(Y) \geq -\frac{1}{n} \Leftrightarrow Y \leq \bar{Y} = \frac{n+m+1}{n+1} \quad (\text{A.1})$$

Notice that $S^*(Y) \leq 1$ is always true for $S^*(0) = \frac{1}{m+1} > 0$. Substituting (3) and (7) into $\Pi_i(q_i, q_{-i}, y_i, y_{-i})$ gives the reduced form of the profit function at the first-stage $\Pi_i(y_i, y_{-i})$. Maximizing $\Pi_i(y_i, y_{-i})$ with respect to y_i for all i yields the first-order condition $\frac{\partial \Pi_i(y_i, y_{-i})}{\partial y_i} = 0$. It is sufficient from concavity of $\Pi_i(y_i, y_{-i})$ in y_i :

$$\frac{\partial^2 \Pi_i(y_i, y_{-i})}{\partial y_i^2} = -2\frac{n^2 + n^2m + nm + n - 1}{n^2(1+m)^2} < 0.$$

Solving this first-order condition for y_i gives the best-reply function $y^r(Y_{-i})$ of downstream gas firm i where $Y_{-i} = \sum_{j \neq i} y_j$:

$$\begin{aligned} y^r(Y_{-i}) &= -\frac{1}{2}\frac{n(n+1)(m+1) - 2Y_{-i}}{n(n+1)(m+1) - 1} \\ &\quad + \frac{1}{2}\frac{n^2(m+1)(n+1) - 2nm - n^2(m+1)^2(n+1)a}{(n+1)(n(n+1)(m+1) - 1)} \end{aligned} \quad (\text{A.2})$$

Then by symmetry $y_i = y$ and $Y_{-i} = (n-1)y$, from (A.2) the Nash equilibrium verifies the linear equation $y^* = y^r((n-1)y^*)$. Solving it gives

$$y^*(a, n, m) = \frac{n(n+1)(m+1) + 2m - n(m+1)^2(n+1)a}{(n+1)(n(n+2)(m+1) + m - 1)}.$$

In addition, for $y^*(a, n, m) \geq 0$ to hold as an equilibrium, a must be satisfied

$$a \leq a_n = \frac{n(n+1)(m+1) + 2m}{n(m+1)^2(n+1)} > 0.$$

If $a > a_n$ then a corner equilibrium arises that if $y^* = 0$, $w^* = \frac{n}{(n+1)(m+1)}$, and $s^* = \frac{1}{m+1}$ therefore $q^* = \frac{n}{(n+1)(m+1)}$. We now check that (A.1) holds since

$$ny^*(a, n, m) - \bar{Y} = -\frac{(m+1)(an^2(m+1) + (n+1)m + 2n - 1)}{n(n+2)(m+1) + m - 1} < 0.$$

Results. Substituting $Y = ny^*(a, n, m)$ into (6) and (7) leads to:

$$w^*(a, n, m) = \frac{n(an(n+1)(m+1) + n - 1)}{(n+1)(n(n+2)(m+1) + m - 1)} > 0 \quad (\text{A.3})$$

$$s^*(a, n, m) = \frac{an(n+1)(m+1) + n - 1}{n(n+2)(m+1) + m - 1} > 0 \quad (\text{A.4})$$

From (A.4), we remark $s^*(a, n, m) > 0$. Moreover the difference

$$s^*(a, n, m) - a = \frac{n - 1 - a(n(m+1) + m - 1)}{n(n+2)(m+1) + m - 1}$$

is linear and decreasing in a , so one can directly see that the solution to the linear equation $s^*(a, n, m) - a = 0$ is $a^* = \frac{n-1}{n(m+1)+m-1}$ then $s^*(a, n, m) \geq a \Leftrightarrow a \leq a^*$. Moreover

$$a_n - a^* = 2m \frac{m + 2n + (m+1)(n+2)n - 1}{n(m+1)^2(n+1)(m+n+mn-1)} > 0$$

hence $a^* < a_n$. Finally substituting (A.4) into (3), supplies in the final market takes equilibrium values

$$q^*(a, n, m) = \frac{m + n(m+1)(1-a)}{n(n+2)(m+1) + m - 1} > 0.$$

Consequently, one can write down the difference $q^*(a, n, m) - y^*(a, n, m)$ to see it is positive

$$q^*(a, n, m) - y^*(a, n, m) = m \frac{n(m+1)(n+1)a + n - 1}{(n+1)(n(n+2)(m+1) + m - 1)} > 0.$$

■

• **Proof of Proposition 2.** The welfare associated with our symmetric equilibrium is quadratic in a and, up to a constant factor in a , $\mathcal{C}_0(c, n, m)$, it writes:

$$W^n(a, c, n, m) = \frac{-n^4(m+1)^2}{2(n(n+2)(m+1) + m - 1)^2} a^2 + \frac{(1+m)n^2[(1+m)(n(m+1)(n+2) + m - 1)c - (n+1)m - 2n + 1]}{(n(m+1)(n+2) + m - 1)^2} a + \mathcal{C}_0(\cdot)$$

It is clearly a concave function of a since

$$\frac{\partial^2 W^n(a, n, m)}{\partial a^2} = \frac{-n^4(m+1)^2}{2(n(n+2)(m+1) + m - 1)^2} < 0.$$

In the case of a corner solution, welfare is independent of a and writes simply

$$W^n(a_n, c, n, m) = \frac{1}{2} \frac{nm(nm + 2m + 2 + 2n)}{(m+1)^2(n+1)^2}.$$

Maximizing $W^n(a, c, n, m)$ with respect to a leads to the optimal solution $a = \min \{ \max \{ a_w^n, 0 \}, a_n \}$ where

$$a_w^n = \frac{n(n+2)(m+1) + m - 1}{n^2}c - \frac{m(n+1) + 2n - 1}{n^2(m+1)}.$$

Moreover $0 \leq a_w^n \leq a_n$ if $c \in [\underline{c}^n, \bar{c}^n]$ with \underline{c}^n (respectively \bar{c}^n) the value of c such that $a_w^n = 0$ (resp. $a_w^n = a_n$). Indeed a_w^n is increasing in c since

$$\frac{da_w^n}{dc} = \frac{n(n+2)(m+1) + m - 1}{n^2} > 0.$$

One can easily find the threshold cost values

$$\bar{c}^n = \frac{m + n + 1}{(n + 1)(m + 1)^2}$$

and

$$\underline{c}^n = \frac{m(n+1) + 2n - 1}{(m+1)(n(n+2)(m+1) + m - 1)}$$

solving for c the respective linear equations $a_w^n = 0$ and $a_w^n = a_n$. Studying the difference $\Delta = \bar{c}^n - \underline{c}^n$ as a function of n and m leads to

$$\frac{d\Delta}{dm} = -\frac{1 + m + 2n}{(1 + m)^3(1 + n)} < 0$$

and

$$\frac{d\Delta}{dn} = -\frac{m}{(1 + m)^2(1 + n)^2} < 0.$$

■.

• **Proof of Proposition 3.** In order to prove this proposition we must first solve the storage subgame. It is itself subdivided into two subgames as a standard Stackelberg game where the leader chooses first y_l^* and the oligopolistic fringe reacts choosing $\vec{\mathbf{1}} \cdot y_f$ both maximizing their respective profits. The aggregate best-reply function of the fringe can be easily inferred from (A.2) solving the equation $y_f = y^r((n-2)y_f + y_l)$ for y_l . After calculations, we obtain

$$Y_{-l}(y_l) = -\frac{n(n+1)(m+1) - 2}{n^2(n+1)(m+1) - 2(n-1)}y_l + \frac{n(n(n+1)(m+1) + 2m) - n^2(m+1)^2(n+1)a}{(n+1)(n^2(n+1)(m+1) - 2(n-1))}$$

Hence, the profit of the leader can be written as follows $\Pi_l(y_l) = \Pi_l(\mathbf{q}, y_l, Y_{-l}(y_l)) = (p^* - S^*)q^* - (a - S^*)y_l$, it is concave in y_l since twice differentiating with respect to y_l leads to

$$\frac{\partial^2 \Pi_l(y_l)}{\partial y_l^2} = -2 \frac{(n+1)^2(n^2(n+1)(m+1) - 2n+1)}{(n^2(n+1)(m+1) - 2n+2)^2} < 0.$$

Maximizing $\Pi_l(y_l)$ in y_l yields storage levels as follows:

$$\hat{y}_l(a, n, m) = \frac{B(n, m) - A(n, m)a}{2(n+1)^2(n^2(n+1)(m+1) - 2(n-1))}$$

and

$$\hat{y}_f(a, n, m) = \frac{Y_{-l}(\hat{y}_l(a, n, m))}{n-1} = \frac{D(n, m) - C(n, m)a}{2(n+1)^2(n^2(n+1)(m+1) - 2(n-1))}$$

where expressions $A(n, m)$, $B(n, m)$, are given by

$$\begin{aligned} A(n, m) &= (m+1)^2 n^5 + 2m(m+1)n^4 + (m+1)^2 n^3 + 2(m+3)n^2 - 4(2n-1), \\ B(n, m) &= (m+1)n^5 + (3m+1)n^3 + 2(2m+3)n^2 - 4(2n-1), \\ C(n, m) &= (m+1)^2 n^4 + 2(m+2)(m+1)n^3 + (m+1)^2 n^2 - 2(m+3)n + 4, \end{aligned}$$

and

$$D(n, m) = (m+1)(n+4)n^3 + (3m+1)n^2 - 2(3n-2),$$

which can be easily seen as positive functions of (n, m) for all $n \geq 2$ and $m \geq 2$. Moreover the denominator of $\hat{y}_l(\cdot)$ and $\hat{y}_f(\cdot)$, $f(n) = n^2(n+1)(m+1) - 2(n-1)$ is positive for all $n \geq 2$ since $f(2) = 12(m+1) - 2 > 0$ and $f'(n) = n(3n+2)(m+1) - 2 > 0$. Hence equilibrium storage levels are nonnegative whenever $a \leq a_l = \frac{B(n, m)}{A(n, m)}$ for $\hat{y}_l(a, n, m)$ and $a \leq a_f = \frac{C(n, m)}{D(n, m)}$ for $\hat{y}_f(a, n, m)$ with $a_l < a_f$ since

$$a_l - a_f = -\frac{4nm(n-1)(n+1)(n^2(n+1)(m+1) - 2n + 1)(n(n+1)(m+1) - 2)}{A(n, m)C(n, m)} < 0.$$

To be admissible, equilibrium values \hat{y}_f and \hat{y}_l must verify condition (4), that is $\hat{Y}(a, n, m) = (n-1)\hat{y}_f(a, n, m) + \hat{y}_l(a, n, m) \leq \bar{Y}$. Writing this difference, it comes

$$\hat{Y}(a, n, m) - \bar{Y} = -\frac{K_0(n, m) + K_1(n, m)a}{2(n+1)(n^2(n+1)(m+1) - 2n + 1)} < 0$$

with

$$K_0(n, m) = (1+m)(n^3(2n+1)(m+1) - n^2(m+3) + 2n) > 0$$

and

$$K_1(n, m) = (1+m)(n^3(2m+3) + n^2(2m+1) - 2(2n-1)) > 0.$$

The condition (4) is then always verified at the equilibrium with leadership.

From (7) in the text, equilibrium price on the market spot is then $\hat{s}(a, n, m) = S^*(\hat{Y}(a, n, m))$ and from (8) on the downstream market, the symmetric equilibrium with leadership corresponds to supplies

$$\hat{q}(a, n, m) = q^*(\hat{s}(a, n, m), n) = \frac{F(n, m) - E(n, m)a}{2(n+1)^2(n^2(n+1)(m+1) - 2n + 1)}$$

with

$$E(n, m) = 2n^3(m+1) + n^2(m+1) - n(3+m) + 2$$

and

$$F(n, m) = 2n^3(m+1) + n^2(2m+1) - 3n + 2 > 0.$$

This supply is nonnegative if $a \leq \bar{a} = \frac{F(n, m)}{E(n, m)}$ where \bar{a} can be easily proved to be greater than a_f .

Equilibrium being established, to complete the proof of the Proposition we just have to study the sign of $z_l(a, n, m) = \hat{y}_l(a, n, m) - q^*(a, n, m)$ that is

$$z_l(a, n, m) = \frac{[B(n, m) - F(n, m)] - [A(n, m) - E(n, m)]a}{2(n+1)^2(n^2(n+1)(m+1) - 2n+1)}$$

with

$$B(n, m) - F(n, m) = (n-1)(n^3(n-1)(m+1) - n^2(2m+3) + 5n - 2)$$

and

$$A(n, m) - E(n, m) = n^5(m+1)^2 + 2n^4(m-1)(m+1) + n^3(m+1)(m-2) + 2n^2(m+4) + n(m-7) + 2.$$

Signing these expressions, one can straightforwardly see that $A(n, m) - E(n, m) > 0$. Concerning the difference $\phi(n) = B(n, m) - F(n, m)$, we study it as a function of n for all $m \geq 2$. Derivatives are then

$$\phi''(n) = (m+1)[20n^3(m+1) + 24n^2(m-1) + 6n(m-2)] + 4(m+4) > 0$$

; $\phi'(n) > 0$ since $\phi'(1) = 156m^2 + 157m + 17 > 0$ and $\phi(n) > 0$ since $\phi(1) = 4m(m+1) > 0$. Hence $B(n, m) - F(n, m) > 0$ and $A(n, m) - E(n, m) > 0$ so it exists $\hat{a}(n, m)$ such that $z_l(\hat{a}, n, m) = 0$ that is

$$\hat{a}(n, m) = \frac{B(n, m) - F(n, m)}{A(n, m) - E(n, m)} > 0.$$

Comparing $\hat{a}(n, m)$ to a_l and $a^*(n, m)$ (defined in Proposition 1 and its proof) leads to (i) $a_l > \hat{a}(n, m)$ since

$$a_l - \hat{a}(n, m) = \frac{2nm(n+1)^2(n^2(n+1)(m+1) - 2(n-1))(n^2(n+1)(m+1) - 2n+1)}{A(n, m)[A(n, m) - E(n, m)]} > 0$$

and (ii) $\hat{a}(n, m) < a^*(n, m)$ since

$$\hat{a}(n, m) - a^*(n, m) = -\frac{2m(n^2-1)(n^2(m+1)(n+1) - 2n+1)}{(n(m+1) + m-1)[A(n, m) - E(n, m)]} < 0$$

■.

• **Proof of Proposition 4.** The welfare function associated with the leadership equilibrium $W^s(a, c, n, m)$ (defined in the text) can be proved to have a quadratic concave profile with respect to a with

$$\frac{\partial^2 W^s}{\partial a^2} = -\frac{1}{4} \frac{n^2(n^2(2n+1)(m+1) - nm - 3n + 2)^2}{(n(n+1)(m+1) - 2n+1)^2(n+1)^2} < 0$$

. Maximizing $W^s(a, c, n, m)$ with respect to a leads to the optimal interior solution $a = \min \{ \max \{ a_w^s, 0 \}, a_l \}$ where

$$a_w^s = 2 \frac{(1+m)(1+n)(n^2(n+2) - 2n+1)}{n(n^2(2n+1)(m+1) + 2 - n(3+m))} c - \frac{n^3(2m+3) + n^2(2m+1) + 2(1-2n)}{n(n^2(2n+1)(m+1) + 2 - n(3+m))}.$$

. To prove Proposition 4 we just have to find values of c for which that $0 \leq a_w^s \leq a^*$. First we look for values of c for which a_w^s lies between 0 and a_l (we already know Proposition 3 that $a^* < a_l$). Then $a_w^s = 0$ if $c = \underline{c}^s$ and $a_w^s = a_l$ if $c = \bar{c}^s$ where

$$\bar{c}^s = \frac{n^4(m+1)(m+n) + n^3(4m+m^2+1) + 2n(3n-4) + 4}{(1+m)G(n, m)} > 0$$

with

$$G(n, m) = n^3(n^2+1)(m+1)^2 + 2n^4m(m+1) + 2n^2(m+3) - 4(2n-1) > 0$$

and

$$\underline{c}^s = \frac{1}{2} \frac{n^3(2m+3) + n^2(2m+1) - 2(2n-1)}{(1+m)(1+n)(n^3+n^3m+n^2+n^2m-2n+1)} > 0$$

. Moreover:

$$\bar{c}^s - \underline{c}^s = \frac{(n^2(2n+1)(m+1) - n(m+3) + 2)n}{2(1+m)(1+n)(n^3+n^3m+n^2+n^2m-2n+1)G(n, m)} \frac{(n^5(m+1) + n^5(3m+1) + 2n^2(2m+3) - 8n + 4)}{2(1+m)(1+n)(n^3+n^3m+n^2+n^2m-2n+1)G(n, m)} > 0$$

But a_w^s is increasing in c since $\frac{da_w^s}{dc} = 2 \frac{(1+m)(1+n)(n^2(n+2) - 2n+1)}{n(n^2(2n+1)(m+1) + 2 - n(3+m))} > 0$ then it is true that $0 \leq a_w^s \leq a_l, \forall c \in [\underline{c}^s, \bar{c}^s]$. Now solving the equation $a_w^s = a^*$ for c in $[\underline{c}^s, \bar{c}^s]$, gives a root $\tilde{c} > 0$:

$$\tilde{c} = \frac{n^5(m+1) + n^4(m+1)(m-2) + n^3(m+2)(m-1) + 8n^2 + n(m-7) + 2}{(m+1)H(n, m)}$$

where $H(n, m) = n^5(m+1)^2 + 2n^4(m-1)(m+1) + n^3(m+1)(m-2) + 2n^2(m+4) + n(m-7) + 2 > 0$. Studying the sign of the following differences we check that $\tilde{c} \in [\underline{c}^s, \bar{c}^s]$.

$$\tilde{c} - \underline{c}^s = \frac{1}{2} \frac{n(n-1)[n^2(m+1)(2n+1) - n(m+3) + 2][n^4 - n^3(m+1) - n^2(2m+3) + 5n - 2]}{H(n, m)(m+1)(n+1)(n^2(m+1)(n+1) - 2(n-1))} > 0$$

$$\bar{c}^s - \tilde{c} = \frac{mn^2[n^2(m+1)(2n+1) - n(m+3) + 2][n^2(m+1)(n+1) - 2(n-1)]}{H(n, m)(m+1)(2n^4m(m+1) + n^3(m+1)^2(n^2+1) + 2n^2(m+3) - 4(2n-1))} > 0$$

Finally, differentiating \tilde{c} in m yields the last result:

$$\begin{aligned} \frac{\partial \tilde{c}}{\partial m} &= -\frac{1}{(1+m)^2 H(n, m)^2} [n^6(n+1)^3 m^4 + 2n^4(n^4 - n^3 + n^2 + 1)(n+1)^2 m^3 + \\ &\quad + n^2(2n^5(3n-8) + 11n^4 + 9n^3 - 13n^2 + 4n + 1)(n+1)^2 m^2 + \\ &\quad + 2n(n+2)(1+n)(n^2(3n-2) + n+1)(n-1)^4 m + \\ &\quad + (n+2)(2n^5 - n^4 - 4n^3 + 10n^2 - 7n + 2)(n-1)^4] < 0 \end{aligned}$$

■.

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