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# A simple equilibrium model for a commodity market with spot trades and futures contracts\*

Ivar Ekeland <sup>†</sup>      Delphine Lautier <sup>‡</sup>      Bertrand Villeneuve <sup>§</sup>

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## Abstract

We propose a simple equilibrium model, where the physical and the derivative markets of the commodity interact. There are three types of agents: industrial processors, inventory holders and speculators. Only the two first of them operate in the physical market. All of them, however, may initiate a position in the paper market, for hedging and/or speculation purposes. We give the necessary and sufficient conditions on the fundamentals of this economy for a rational expectations equilibrium to exist and we show that it is unique. This is the first contribution of the paper. Our model exhibits a surprising variety of behaviours at equilibrium, and our second contribution is that the paper offers a unique generalized framework for the analysis of price relationships. The model indeed allows for the generalization of hedging pressure theory, and it shows how this theory is connected to the storage theory. Meanwhile, it allows to study simultaneously the two main economic functions of derivative markets: hedging and price discovery. In its third contribution, through the distinction between the utility of speculation and that of hedging, the model illustrates the interest of a derivatives market in terms of the welfare of the agents.

JEL Codes: D40; D81; D84; G13; Q00.

## 1 Introduction

In the field of commodity derivative markets, some questions are as old as the markets themselves,... and they remain open today. Speculation is a good example: as early as in 1939, in his famous article about speculation and economic activity, Kaldor wrote: "Does

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speculation exert a price-stabilising influence, or the opposite? The most likely answer is that it is neither, or rather that it is both simultaneously". More than 70 years later, in June 2011, the report of the G20 states: "The debate on whether speculation stabilizes or destabilizes prices resumes with renewed interest and urgency during high price episodes. [...] More research is needed to clarify these questions and in so doing to assist regulators in their reflections about whether regulatory responses are needed and the nature and scale of those responses." Our simple (perhaps the simplest possible) model of commodity trading provides insights into this question. It also proposes a way to understand how these markets function and how the futures and spot prices are formed. Finally, it illustrates the interest of a derivative market in terms of the welfare of the agents.

In this model, the financial market interacts with the physical market. There are two periods, a single commodity, a numéraire, and two markets: the spot market at time  $t = 1$  and  $t = 2$ , and the futures market, which is open at  $t = 1$  and settled at  $t = 2$ . The spot market is physical (no shorting is allowed: there is a non negativity constraint on inventories), while the futures market is financial (both long and short positions are allowed). There are three types of traders: inventory holders and industrial processors of the commodity, both of which operate on the two markets, and speculators, who operate on the futures market only. All of them are utility maximizers, and have mean-variance utility (more about this later on). There is also a background demand (or supply), attributed to spot traders, which helps clear the spot markets. The sources of uncertainty are the amount of commodity produced and the demand of the spot traders at  $t = 2$ : their realization is unknown at  $t = 1$ , but their law is common knowledge. As only the difference between these two quantities matters, there is only one source of uncertainty. All decisions are taken at  $t = 1$ , conditionally on expectations about  $t = 2$ .

Our main contributions are three: qualitative, quantitative and normative. They are the consequences of the tractability of the model.

Qualitatively, despite the presence of highly non linear equilibrium equations, we give necessary and sufficient conditions on the fundamentals of this economy for a rational expectations equilibrium to exist and we show that it is unique. Moreover, it has a very interesting economic interpretation. It provides us, indeed, with a unified framework for the theory of price relations in commodity futures markets, whereas in the literature the analysis is usually split into two strands: the storage theory and the normal backwardation theory (also named the hedging pressing theory <sup>1</sup>). The first focuses on the cost of storage of the underlying asset, the second on the risk premium. Although they are complementary, to the best of our knowledge these two strands remained apart up to now.

With our model, we characterize four possible regimes in equilibrium, given the non-negativity constraints on physical positions and on prices. While each of these four regimes is simple to understand on economical grounds, we believe that our model is the first to allow them and to give explicit conditions on the fundamentals of the economy determining which one will actually prevail in equilibrium. In each of the regimes, we also give explicit formulas for the equilibrium prices. This enables us to characterize regimes in detail and to perform complete and novel comparative statics. For instance, as is done in the storage theory, we can explain why there is a contango (the "current basis", defined as the difference between the futures price and the *current* spot price, is positive) or a

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<sup>1</sup>see for example JOF 2000

backwardation (the current basis is negative) on the futures market. Towards this analysis, we give insights into the question of the informational content of the futures price and the price discovery function of futures markets. As done in the normal backwardation theory, we can also compare the futures price with the expected spot price and ask whether or not there is a bias in the futures price (we define the “expected basis” as the difference between the futures price and the *expected* spot price). The sign and the level of the bias depend directly on which regime prevails. In the third one, for instance, there is no bias; in the first regime, there are two sub-regimes, one where the futures price is higher than the expected spot price, and one where it is lower. Here, the model depicts the way futures market are used to reallocate risk between operators, the price to pay for such a transfer, and thus provides insights into the main economic function of derivative markets: hedging.

On a quantitative point of view, our model allows for an important number of comparative statics. We show that as the importance of speculators in the futures market increases, for example because access to the market is relaxed, the volatility of prices goes up. This effect may sound inefficient. Our interpretation is that speculation increases the informativeness of prices: volatility brings more efficiency. The mechanism is quite simple. As the number of speculators increases, the cost of hedging decreases and demand for futures grows along with physical positions. Smaller hedging costs make storers and processors amplify the differences in their positions in response to different pieces of information, implying that their market impact increases. This increases in turn the volatility of prices.

Normatively, we use our model to perform a welfare analysis. This question, again, is as old as derivatives markets. Newberry (2008) summarizes well the usual yet dual appreciation of the impact of derivatives markets on welfare. Newberry makes a difference between what he call the "layman" and "the body of informed opinion". He explains that, to the first of them, "the association of speculative activity with volatile markets is often taken as proof that speculators are the cause of the instability", whereas to the second, "volatility creates a demand for hedging or insurance". Our model also exhibits a dual conclusion about welfare, but it is differently stated. First, the model allows for a clear separation between the utility of speculation and that of hedging. Then, the analysis of the impact of an increasing number of speculators shows that, storers and processors, as far as their hedging activities are concerned, have opposite views on the desirability of speculators. The latter are worthless when the positions of storers and processors match exactly; but when one type of agents has more needs than the other type can supply, then the former wants more (the latter wants less) speculators because this reduces the cost of hedging for those who need it most. To the best of our knowledge, such an effect has never been investigated before.

**Short literature review** Of course, the questions we have raised have been investigated before. Contrary to what is done in this paper, the literature on commodity prices however separates the question of the links between the spot and the futures prices and that of the bias in the futures price. The latter has been investigated first by Keynes (1930) through the theory of normal backwardation (hedging pressure theory) whereas the former is usually associated to the theory of storage, initiated by Kaldor (1940), Brennan (1958) and Working (1949). The same is true for the equilibrium models developed so far.

An important number of equilibrium models of commodity prices focuses on the bias in the futures price and the risk transfer function of the derivative market. This is the

case, for example, of [Anderson and Danthine \(1983a\)](#), [Anderson and Danthine \(1983b\)](#), [Hirshleifer \(1988\)](#), [Hirshleifer \(1989\)](#), [Guesnerie and Rochet \(1993\)](#), and [Acharya et al. \(2011\)](#). [Anderson and Danthine \(1983a\)](#) is an important source. Compared with this work, our model is more simple (the producers are not directly modeled) and completely specified. This gives us the possibility to obtain explicit formulas for the equilibrium prices and to investigate further economics issues, like welfare for example. The models developed by [Hirshleifer \(1988\)](#) and [Hirshleifer \(1989\)](#) are also inspired by [Anderson and Danthine \(1983a\)](#). In these papers, Hirshleifer analyzes two points which are interesting for our model but that we did not take the time to develop: first, the simultaneous existence of futures and forward markets; second, the role of the spot traders. [Hirshleifer \(1989\)](#) also asks whether or not vertical integration and futures trading can be substitute means of diversifying risk. We focus instead, in the comparative statics, on the impact by type of agent, with a rich variety of cases.

Let us also mention that, contrary to [Anderson and Danthine \(1983b\)](#), [Hirshleifer \(1989\)](#) and [Routledge et al. \(2000\)](#), we do not undertake an inter-temporal analysis in the present version of the model. [Anderson and Danthine \(1983b\)](#) is the extension of [Anderson and Danthine \(1983a\)](#). To obtain results while keeping tractable equations, the authors however must simplify their model so that only one category of hedger remains in the inter-temporal version. When equilibrium analysis stands at the heart of all concerns (which is our case), this is a strong limitation. [Routledge et al. \(2000\)](#) give another interesting example of inter-temporal analysis. It is however not adapted to normative analysis.

Beyond the question of the risk premium, equilibrium models have also been used in order to examine the possible destabilizing effect of the presence of a futures market and to analyze welfare issues. This is the case of [Guesnerie and Rochet \(1993\)](#), [Newbery \(1987\)](#), and [Baker and Routledge \(2012\)](#). As the model proposed by [Guesnerie and Rochet \(1993\)](#) is devoted to the analysis of mental (“eductive”) coordination strategies, it is more stripped down than ours. As in [Newbery \(1987\)](#), our explicit formulas for equilibrium prices allows for interesting comparisons depending on the presence or absence of a futures market. Finally, contrary to [Baker and Routledge \(2012\)](#), we are not interested in Pareto optimal risk allocations.

Another strand of the literature on equilibrium models focuses on the *current* spot price and the role of inventories in the behavior of commodity prices, as in [Deaton and Laroque \(1992\)](#), and in [Chambers and Bailey \(1996\)](#). In these models, however, there are no futures market; there is in fact a single type of representative agent, which prevents examining risk allocation and the political economy of structural change.

Apart from the specific behavior of prices, the non-negativity constraint on inventories raises another issue. Empirical facts indeed testify that there is more than a non-negativity constraint in commodity markets: the level of inventories never falls to zero, leaving thus unexploited some supposedly profitable arbitrage opportunities. The concept of a convenience yield associated with inventories, initially developed by [Kaldor \(1940\)](#) and [Brennan \(1958\)](#) is generally used to explain such a phenomenon, which has been regularly confirmed, on an empirical point of view, since [Working \(1949\)](#). In their model, [Routledge et al. \(2000\)](#) introduce a convenience yield in the form of an embedded timing option associated with physical stocks. Contrary to these authors, we do not take into account the presence of a convenience yield in our analysis. While this would probably constitute an interesting improvement of our work, it is hardly compatible with a two-period model.

Recent attempts to test equilibrium models must also be mentioned, as they are rare. While not totally operable in our context, the tests undertaken by [Acharya et al. \(2011\)](#) could be used as in fruitful source of inspiration for further developments of our model. As far the analysis of the risk premium is concerned, the empirical tests performed by [Hamilton and Wu \(2012\)](#) and the simulations proposed by [Bessembinder and Lemmon \(2002\)](#) are other possible directions.

## 2 The model

This is a two-period model. There is one commodity, a numéraire, and two markets: the spot market at times  $t = 1$  and  $t = 2$ , and a futures market, which is open at  $t = 1$  and such that contracts are settled at time  $t = 2$ . It is important to note that short positions are allowed on the futures market. When an agent sells (resp. buys) futures contracts, his position is short (resp. long), and the amount  $f$  he holds is negative (resp. positive). On the spot market, such positions are not allowed: you can't sell what you don't hold. In other words, the futures is a financial market, while the spot is a physical market.

There are three types of traders.

- *Industrial users*, or processors, who use the commodity to produce other goods which they sell to consumers. Because of the inertia of their own production process, and/or because all their production is sold forward, they decide at  $t = 1$  how much to produce at  $t = 2$ . They cannot store the commodity, so they have to buy all of their input on the spot market at  $t = 2$ . They also trade on the futures market.
- *Inventory holders*, who have storage capacity, and who can use it to buy the commodity at  $t = 1$  and release it at  $t = 2$ . They trade on the spot market at  $t = 1$ , where they buy, and at  $t = 2$ , where they sell. They also operate on the futures market.
- *Money managers*, or speculators, who use the commodity price as a source of risk, to make a profit on the basis of their positions in futures contracts. They do not trade on the spot market.

In addition, we think of these markets as operating in a partial equilibrium framework: in the background, there are other users of the commodity, and producers as well. These additional agents will be referred to as *spot traders*, and their global effect will be described by a demand function. At time  $t = 1$ , the demand is  $\mu_1 - mP_1$ , and it is  $\tilde{\mu}_2 - m\tilde{P}_2$  at time  $t = 2$ .  $P_t$  is the spot price at time  $t$  and the demand can be either positive or negative; the sign  $\sim$  indicates a random variable.

All decisions are taken at time  $t = 1$ , conditional on the information available for  $t = 2$ . The timing is as follows:

- for  $t = 1$ , the commodity is in total supply  $\omega_1$ , the spot market and the futures market open. On the spot market, there are spot traders and storers on the demand side, the price is  $P_1$ . On the futures markets, the processors, the storers and the speculators all initiate a position, and the price is  $P_F$ . Note that the storers have to decide simultaneously how much to buy on the spot market and what position to take on the futures market.

- for  $t = 2$ , the commodity is in total supply  $\tilde{\omega}_2$ , to which one has to add the inventory which the storers carry from  $t = 1$ , and the spot market opens. The processors and the spot traders are on the demand side, and the price is  $\tilde{P}_2$ . The futures contracts are then settled at that price, meaning that every contract brings a financial result of  $\tilde{P}_2 - P_F$ .

There are  $N_S$  speculators,  $N_P$  processors,  $N_I$  storage companies ( $I$  for inventories). We assume that all agents (except the spot traders) are risk averse inter-temporal utility maximizers. To take their decisions at time  $t = 1$ , they need to know the distribution of the spot price  $\tilde{P}_2$  at  $t = 2$ . We will show that, under mean-variance specifications of the utilities, there is a unique price system  $(P_1, P_F, \tilde{P}_2)$  such that all three markets clear.

Uncertainty is modeled by a probability space  $(\Omega, \mathcal{A}, P)$ . Both  $\tilde{\omega}_2$ ,  $\tilde{\mu}_2$  and  $\tilde{P}_2$  are random variables on  $(\Omega, \mathcal{A}, P)$ . At time  $t = 1$ , their realizations are unknown, but their distributions are common knowledge.

Before we proceed, some clarifications are in order.

- Production of the commodity is inelastic: the quantities  $\omega_1$  and  $\tilde{\omega}_2$  which reach the spot markets at times  $t = 1$  and  $t = 2$  are exogenous to the model. Traders know  $\omega_1$  and  $\mu_1$ , and share the same priors as to  $\tilde{\omega}_2$  and  $\tilde{\mu}_2$ .
- This said, a negative spot demand can be understood as extra spot supply: if for instance  $P_1 > \mu_1/m$ , then the spot price at time  $t = 1$  is so high that additional means of production become profitable, and the global economy provides additional quantities to the spot market. The coefficient  $m$  is the elasticity of demand (or production) with respect to prices. The number  $\mu_1$  (demand when  $P_1 = 0$ ) is the level at which the economy saturates: to induce spot traders to demand quantities larger than  $\mu_1$ , one would have to pay them, that is, offer negative price  $P_1 < 0$  for the commodity. The same remark applies to time  $t = 2$ .
- We separate the roles of the industrial user and the inventory holder, whereas in reality industrial users may also hold inventory. It will be apparent in the sequel that this separation need not be as strict, and that the model would accommodate agents of mixed type. In all cases, agents who trade on the physical markets would also trade on the financial market for two separate purposes: hedging their risk, and making additional profits. In the sequel, we will see how their positions reflect this dual purpose.
- Note also that the speculators would typically use their position on the futures market as part of a diversified portfolio; our model does not take this into account.
- We also suppose that there is a perfect convergence of the basis at the expiration of the futures contract. Thus, at time  $t = 2$ , the position on the futures markets is settled at the price  $\tilde{P}_2$  then prevailing on the spot market.
- For the sake of simplicity, we set the risk-free interest rate to 0.

In what follows, as we examine an REE (rational expectation equilibrium), we look at two necessary conditions for such an equilibrium to appear: the maximization of the agent's utility, conditionally on their price expectations, and market clearing.



### 3 Optimal positions and market clearing

#### 3.1 Profit maximization

All agents have mean-variance utilities. For all of them, a profit  $\tilde{\pi}$  brings utility:

$$E[\tilde{\pi}] - \frac{1}{2}\alpha_i \text{Var}[\tilde{\pi}] \tag{1}$$

where  $\alpha_i$  is the risk aversion parameter of a type  $i$  individual.

Beside their mathematical tractability, there are good economic reasons for using mean-variance utilities. They are not of von Neumann - Morgenstern type, i.e formula (1) cannot be put in the form  $E[u(\tilde{X})]$  for a suitable function  $u$ , so they are poorly suited to model the behaviour of individuals under uncertainty. However, they are well suited to describe the behaviour of firms operating under risk constraints. The capital asset-pricing model (CAPM) in finance, for instance, consists of maximizing  $E[\tilde{R}]$  under the constraint  $\text{Var}[\tilde{R}] \leq \rho$ , where  $\tilde{R}$  is the return on the portfolio, which is equivalent to maximizing  $E[\tilde{R}] - \lambda \text{Var}[\tilde{R}]$ , where  $\lambda$  is the Lagrange multiplier. In financial markets, as in commodities markets, agents are mostly firms, not individuals, and they have risk constraints imposed on them from inside (managers controlling traders) and from outside (regulators controlling the firm). This is what formula (1) is trying to capture. For the sake of simplicity, we have kept the variance as a measure of risk, but we expect that our results could be extended to more sophisticated ones (coherent risk measures), at the cost of some mathematical complications.

**Speculator** For the speculator, the profit resulting from a position in the futures market  $f_S$  is the r.v.:

$$\pi_S(f_S) = f_S (\tilde{P}_2 - P_F),$$

and the optimal position is:

$$f_S^* = \frac{E[\tilde{P}_2] - P_F}{\alpha_S \text{Var}[\tilde{P}_2]}. \tag{2}$$

This position is purely speculative. It depends mainly on the level and on the sign of the bias in the futures price. The speculator goes long whenever he thinks that the expected spot price is higher than the futures price. Otherwise he goes short. Finally, he is all the more inclined to take a position as his risk aversion and volatility of the underlying asset are low.

**Storer** The storer can hold any non-negative inventory. However, storage is costly: holding a quantity  $x$  between  $t = 1$  and  $t = 2$  costs  $\frac{1}{2}Cx^2$ . Parameters  $C$  (cost of storage) and  $\alpha_I$  (risk aversion) characterize the storer. He has to decide how much inventory to buy at  $t = 1$ , if any, and what position to take in the futures market, if any.



If he buys  $x \geq 0$  on the spot market at  $t = 1$ , resells it on the spot market at  $t = 2$ , and takes a position  $f_I$  on the futures market, the resulting profit is the r.v.:

$$\pi_I(x, f_I) = x(\tilde{P}_2 - P_1) + f_I(\tilde{P}_2 - P_F) - \frac{1}{2}Cx^2.$$

The optimal position on the physical market is:

$$x^* = \frac{1}{C} \max\{P_F - P_1, 0\}. \quad (3)$$

The storer holds inventories if the futures price is higher than the current spot price. This position is the only one, in the model, that directly links the spot and the futures prices. This is consistent with the theory of storage and, more precisely, its analysis of contango and the informational role of futures prices.

The optimal position on the futures market is:

$$f_I^* = \frac{E[\tilde{P}_2] - P_F}{\alpha_I \text{Var}[\tilde{P}_2]} - x^*. \quad (4)$$

This position can be decomposed into two elements. First, a negative position  $-x^*$ , which simply hedges the physical position: the storer sells futures contracts in order to protect himself against a decrease in the spot price. Second, a speculative position, structurally identical to that of the speculator, which reflects the storer's risk aversion and his expectations about the relative level of the futures and the expected spot prices.

**Processor** The processor decides at time  $t = 1$  how much input  $y$  to buy at  $t = 2$ , and which position  $f_P$  to take on the futures market. The revenue from sales at date  $t = 2$  is  $(y - \frac{\beta}{2}y^2)P$ , where  $P$  is our convention for the forward price of the output, and the other factor reflects decreasing marginal revenue. Due to these forward sales of the production, this revenue is known at time  $t = 1$ . The resulting profit is the r.v.:

$$\pi_P(y, f_P) = \left(y - \frac{\beta}{2}y^2\right)P - y\tilde{P}_2 + f_P(\tilde{P}_2 - P_F).$$

An easy computation then gives his optimal decisions, namely:

$$y^* = \frac{1}{\beta P} \max\{P - P_F, 0\}, \quad (5)$$

$$f_P^* = \frac{E[\tilde{P}_2] - P_F}{\alpha_P \text{Var}[\tilde{P}_2]} + y^*. \quad (6)$$

The futures market is also used by the processor to plan his production, all the more so if the price of his input  $P_F$  is below that of his output  $P$ . The position on the futures market, again, can be decomposed into two elements. First, a positive position  $y^*$ , which hedges the position on the physical market: the processor goes long on futures contracts in order to protect himself against an increase in the spot price. Then, a speculative position reflecting the processor's risk aversion and his expectations about the level of the expected basis.

**Remarks on optimal positions** In this framework, all agents have the possibility to undertake speculative operations. After having hedged 100 percent of their physical positions, they adjust this position according to their expectations. The separation of the physical and the futures decisions was derived by [Danthine \(1978\)](#). As shown by [Anderson and Danthine \(1983a\)](#), this property does not hold if the final good price is stochastic, unless a second futures market for the final good is introduced. As we shall see, this separation result is very convenient for equilibrium analysis. This is one of the reasons why we choose, for the processor, not to introduce uncertainty on the output price and/or on the quantities produced.

### 3.2 Market clearing

Although we assume that all individuals are identical in each category of agents, more subtle assumptions could be retained without much complication. For example, remark that if the storers had different technologies, say, storer  $i$  with  $i = 1, \dots, N_I$  had technology  $C_i$ , then, instead of  $\frac{N_I}{C} \max\{P_F - P_1, 0\}$ , total inventories would be  $(\sum_i 1/C_i) \max\{P_F - P_1, 0\}$ . In other words, storers are easily aggregated. In the following, when relevant, we shall use the index  $n_I$  representing a synthetic number of storage units, and per-unit inventories  $X^*$  defined by:

$$n_I = \begin{cases} N_I/C & \text{if storers are identical,} \\ \sum_i 1/C_i & \text{otherwise,} \end{cases}$$

$$X^* = \max\{P_F - P_1, 0\}.$$

Similarly, if processors had different technologies, say, processor  $i$  with  $i = 1, \dots, N_P$  had technology  $\beta_i$ , then total input demand would be  $\sum_i 1/(\beta_i P) \cdot \max\{P - P_F, 0\}$  instead of  $\frac{N_P}{\beta P} \max\{P - P_F, 0\}$ . Thus, when relevant, we shall use the index  $n_P$  representing a synthetic number of processing units, and per-unit demand  $Y^*$  defined by:

$$n_P = \begin{cases} \frac{N_P}{\beta P} & \text{if processors are identical,} \\ \frac{1}{P} \sum_i \frac{1}{\beta_i} & \text{otherwise,} \end{cases}$$

$$Y^* = \max\{P - P_F, 0\}.$$

**The spot market at time 1** On the supply side we have the harvest  $\omega_1$ . On the other side we have the inventory  $n_I X^*$  bought by the storers, and the demand of the spot traders. Market clearing requires:

$$\omega_1 = n_I X^* + \mu_1 - m P_1,$$

hence:

$$P_1 = \frac{1}{m} (\mu_1 - \omega_1 + n_I X^*). \quad (7)$$

**The spot market at time 2** We have, on the supply side, the harvest  $\tilde{\omega}_2$ , and the inventory  $n_I X^*$  sold by the storers; on the other side, the input  $n_P Y^*$  bought by the processors and the demand of the spot traders. The market clearing condition is:

$$\tilde{\omega}_2 + n_I X^* = n_P Y^* + \tilde{\mu}_2 - m \tilde{P}_2,$$

with  $X^*$  and  $Y^*$  as above. We get:

$$\tilde{P}_2 = \frac{1}{m} (\tilde{\mu}_2 - \tilde{\omega}_2 - n_I X^* + n_P Y^*). \quad (8)$$

**The futures market** Market clearing requires:

$$N_S f_S^* + N_P f_P^* + N_I f_I^* = 0.$$

Replacing the  $f_i^*$  by their values, we get:

$$E[\tilde{P}_2] - P_F = \frac{\text{Var}[\tilde{P}_2]}{\frac{N_P}{\alpha_P} + \frac{N_I}{\alpha_I} + \frac{N_S}{\alpha_S}} (n_I X^* - n_P Y^*). \quad (9)$$

Remark that if, say, different storers had different risk aversions  $\alpha_{Ij}$  (for  $j = 1, \dots, N_I$ ), then we would see  $\sum_j 1/\alpha_{Ij}$  instead of  $N_I/\alpha_I$  in equation (9). This is an illustration of a more general fact: we sum up the inverse of the risk aversions of all agents to represent the inverse of the overall (or market) risk aversion.

Equation (9) gives a formal expression for the bias in the futures price, which confirms the findings of [Anderson and Danthine \(1983a\)](#). It shows indeed that the bias depends primarily on fundamental economic structures (the characteristics of the storage and production functions, which are embedded in  $X^*$  and  $Y^*$ ) and the number of operators, secondarily on subjective parameters (the risk aversion of the operators), and thirdly on the volatility of the underlying asset. Note also that the sign of the bias depends only on the sign of  $(n_I X^* - n_P Y^*)$ . As the risk aversion of the operators only influences the speculative part of the futures position, it does not impact this sign. Finally, when  $n_I X^* = n_P Y^*$ , there is no bias in the futures price, and the risk transfer function is entirely undertaken by the hedgers, provided that their positions on the futures market are the exact opposite of each others. Thus the absence of bias is not exclusively the consequence of risk neutrality but may have other structural causes.

## 4 Existence and uniqueness of the equilibrium

The equations characterizing the equilibrium are the optimal choices on the physical market (equations (3) and (5)), the clearing of the spot market at dates 1 and 2 (equations (7) and (8)), as well as the clearing of the futures market (9):

$$\left\{ \begin{array}{l} X^* = \max\{P_F - P_1, 0\} \quad (3) \\ Y^* = \max\{P - P_F, 0\} \quad (5) \\ P_1 = \frac{1}{m} (\mu_1 - \omega_1 + n_I X^*) \quad (7) \\ \tilde{P}_2 = \frac{1}{m} (\tilde{\mu}_2 - \tilde{\omega}_2 - n_I X^* + n_P Y^*) \quad (8) \\ P_F = E[\tilde{P}_2] + \frac{\text{Var}[\tilde{P}_2]}{\frac{N_P}{\alpha_P} + \frac{N_I}{\alpha_I} + \frac{N_S}{\alpha_S}} (n_P Y^* - n_I X^*) \quad (9) \end{array} \right.$$

Let us also remind that the distribution of  $\tilde{\mu}_2 - \tilde{\omega}_2$  is common knowledge. We introduce the following notations:

$$\xi_1 := \mu_1 - \omega_1,$$

$$\begin{aligned}\tilde{\xi}_2 &:= \tilde{\mu}_2 - \tilde{\omega}_2, \\ \xi_2 &:= \mathbb{E}[\tilde{\mu}_2 - \tilde{\omega}_2], \\ \rho &:= 1 + m \frac{\text{Var}[\tilde{\mu}_2 - \tilde{\omega}_2]}{\frac{N_P}{\alpha_P} + \frac{N_I}{\alpha_I} + \frac{N_S}{\alpha_S}}\end{aligned}$$

where  $m$  is the elasticity of demand.

From (8), we can derive useful moments:

$$\mathbb{E}[\tilde{P}_2] = \frac{1}{m} (\xi_2 - n_I X^* + n_P Y^*), \quad (8E)$$

$$\text{Var}[\tilde{P}_2] = \frac{\text{Var}[\tilde{\xi}_2]}{m^2}. \quad (8V)$$

We assume  $\text{Var}[\tilde{\xi}_2] > 0$ , so there is uncertainty on the future availability of the commodity. It is the only source of uncertainty in the model. Likewise, we assume (for the time being) that  $\alpha_P, \alpha_I$  and  $\alpha_S$  all are non-zero numbers. These restrictions will be lifted later on.

## 4.1 Definitions

**Definition 1.** An *equilibrium* is a family  $(X^*, Y^*, P_1, P_F, \tilde{P}_2)$  such that all prices are non-negative, processors, storers and speculators act as price-takers, and all markets clear.

Technically speaking,  $(X^*, Y^*, P_1, P_F, \tilde{P}_2)$  is an equilibrium if equations (3), (5), (7), (8), and (9) are satisfied, with  $X^* \geq 0$ ,  $Y^* \geq 0$ ,  $P_1 \geq 0$ ,  $P_F \geq 0$  and  $\tilde{P}_2(\omega) \geq 0$  for all  $\omega \in \Omega$ . Note that the latter condition depends on the realization of the random variable  $\tilde{P}_2$ , which can be observed only at  $t = 2$ , while the first four can be checked at time  $t = 1$ . This leads us to the following:

**Definition 2.** A *quasi-equilibrium* is a family  $(X^*, Y^*, P_1, P_F, \tilde{P}_2)$  such that all prices except possibly  $\tilde{P}_2$  are non-negative, processors, storers and speculators act as price-takers and all markets clear.

Technically speaking, a quasi-equilibrium is a family  $(X^*, Y^*, P_1, P_F, \tilde{P}_2) \in \mathbb{R}_+^4 \times L^0(\Omega, \mathcal{A}, P)$  such that equations (3), (5), (7), (8) and (9) are satisfied.

We now give two existence and uniqueness results, the first one for quasi-equilibria and the second one for equilibria.

## 4.2 Quasi-equilibrium

**Theorem 1.** *There is a quasi-equilibrium if and only if  $(\xi_1, \xi_2)$  belongs to the region:*

$$\xi_2 \geq -\rho n_P P \quad \text{if } \xi_1 \geq 0, \quad (10)$$

$$\xi_2 \geq -\rho n_P P - ((m + \rho n_P)/n_I + \rho) \xi_1 \quad \text{if } -n_I P \leq \xi_1 \leq 0, \quad (11)$$

$$\xi_2 \geq -(m/n_I + \rho) \xi_1 \quad \text{if } \xi_1 \leq -n_I P, \quad (12)$$

and then it is unique.

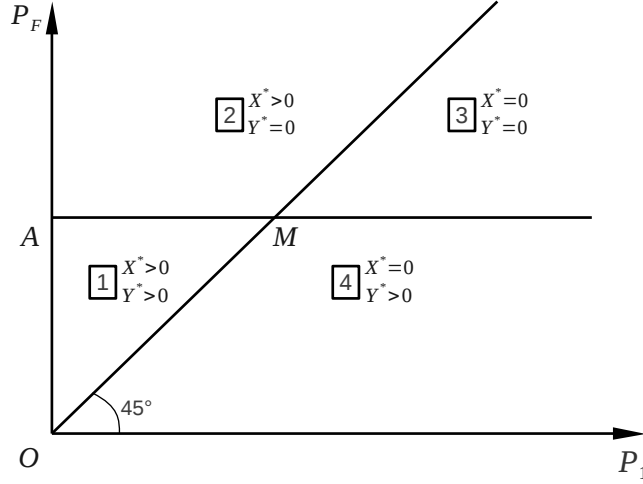


Figure 1: Phase diagram of physical and financial decisions in space  $(P_1, P_F)$ .

*Proof.* To prove this theorem, we begin by substituting equation (8E) in equation (9). We get:

$$mP_F - \rho(n_P Y^* - n_I X^*) = \xi_2. \quad (13)$$

We now have two equations, (7) and (13) for  $P_1$  and  $P_F$ . Replacing  $X^*$  and  $Y^*$  by their values, given by (3) and (5), we get a system of two nonlinear equations in two variables:

$$mP_1 - n_I \max\{P_F - P_1, 0\} = \xi_1, \quad (14)$$

$$mP_F + \rho(n_I \max\{P_F - P_1, 0\} - n_P \max\{P - P_F, 0\}) = \xi_2. \quad (15)$$

Remark that if we can solve this system with  $P_1 > 0$  and  $P_F > 0$ , we get  $\tilde{P}_2$  from (8). So the problem is reduced to solving (15) and (14). Consider the mapping  $F : \mathbb{R}_+^2 \rightarrow \mathbb{R}^2$  defined by:

$$F(P_1, P_F) = \begin{pmatrix} mP_1 - n_I \max\{P_F - P_1, 0\} \\ mP_F + \rho(n_I \max\{P_F - P_1, 0\} - n_P \max\{P - P_F, 0\}) \end{pmatrix}.$$

In  $\mathbb{R}_+^2$ , take  $P_1$  as the horizontal coordinate and  $P_F$  as the vertical one, as depicted by Figure 1. There are four regions, separated by the straight lines  $P_F = P_1$  and  $P_F = P$ :

- Region 1, where  $P_F > P_1$  and  $P_F < P$ . In this region, both  $X^*$  and  $Y^*$  are positive.
- Region 2, where  $P_F > P_1$  and  $P_F > P$ . In this region,  $X^* > 0$  and  $Y^* = 0$ .
- Region 3, where  $P_F < P_1$  and  $P_F > P$ . In this region,  $X^* = 0$  and  $Y^* = 0$ .
- Region 4, where  $P_F < P_1$  and  $P_F < P$ . In this region,  $X^* = 0$  and  $Y^* > 0$ .

Moreover, in the regions where  $X^* > 0$ , we have  $X^* = P_F - P_1$  and in the regions where  $Y^* > 0$ , we have  $Y^* = P - P_F$ . So, in each region, the mapping is linear, and it is obviously continuous across the boundaries. Denote by  $O$  the origin in  $\mathbb{R}_+^2$ , by  $A$  the

point  $P_1 = 0$ ,  $P_F = P$ , and by  $M$  the point  $P_1 = P_F = P$  (so, for instance, region 1 is the triangle  $OAM$ ). In region 1, we have:

$$F(P_1, P_F) = \begin{pmatrix} mP_1 - n_I(P_F - P_1) \\ mP_F + \rho(n_I(P_F - P_1) - n_P(P - P_F)) \end{pmatrix}.$$

The images  $F(O)$ ,  $F(A)$ , and  $F(M)$  are easily computed:

$$\begin{aligned} F(O) &= (0, -\rho n_P P), \\ F(A) &= P(-n_I, m + \rho n_I), \\ F(M) &= mP(1, 1). \end{aligned}$$

From this, one can find the images of all four regions (see Figure 2). The image of region 1 is the triangle  $F(O)F(A)F(M)$ . The image of region 2 is bounded by the segment  $F(A)F(M)$  and by two infinite half-lines, one of which is the image of  $\{P_1 = 0, P_F \geq P\}$ , the other being the image of  $\{P_1 = P_F, P_F \geq P\}$ . In region 2, we have:

$$F(P_1, P_F) = \begin{pmatrix} mP_1 - n_I(P_F - P_1) \\ mP_F + \rho n_I(P_F - P_1) \end{pmatrix}.$$

The first half-line emanates from  $F(A)$  and is carried by the vector  $(-n_I, m + \rho n_I)$ . The second half-line emanates from  $F(M)$  and is carried by the vector  $(1, 1)$ . Both of them (if extended in the negative direction) go through the origin. The image of region 4 is bounded by the segment  $F(O)F(M)$  and by two infinite half-lines, one of which is the image of  $\{P_F = 0\}$ , the other being the image of  $\{P_1 \geq P, P_F = P\}$ . In region 4, we have:

$$F(P_1, P_F) = \begin{pmatrix} mP_1 \\ mP_F - \rho n_P(P - P_F) \end{pmatrix},$$

so the first half-line emanates from  $F(O)$  and is horizontal, with vertical coordinate  $-\rho n_P P$ , and the second emanates from  $F(M)$  and is horizontal. The image of region 3 is entirely contained in  $\mathbb{R}_+^2$ , where it is the remainder of the three images we described. To prove the theorem, we have to show that the system (15) and (14) has a unique solution. It can be rewritten as:

$$F(P_1, P_F) = \begin{pmatrix} \xi_1 \\ \xi_2 \end{pmatrix},$$

and it has a unique solution if and only if the right-hand side belongs to the image of  $F$ , which we have just described. This leads to the conclusion of the proof: based on the previous remark summarized in Figure 2, we easily find the expressions of the theorem.  $\square$

### 4.3 Equilibrium

To get an equilibrium instead of a quasi-equilibrium, we need the further condition, calculated last,  $\tilde{P}_2 \geq 0$ . By equation (8), this is equivalent to:

$$\inf \{\tilde{\mu}_2 - \tilde{\omega}_2\} \geq n_I X^* - n_P Y^*. \quad (16)$$

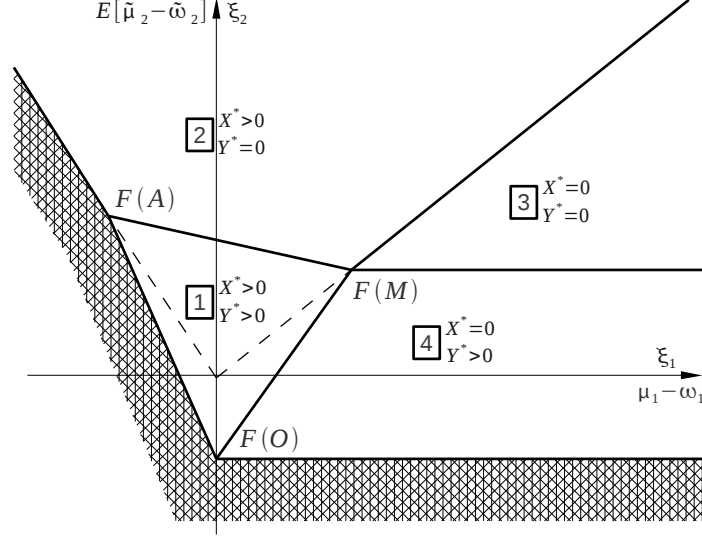


Figure 2: Phase diagram of physical and financial decisions.

This amount to

$$P_F \leq \frac{\inf \{\tilde{\mu}_2 - \tilde{\omega}_2\} + n_I P_1 + n_P P}{n_I + n_P} \quad \text{in region 1,} \quad (17)$$

$$P_F \leq P_1 + \frac{\inf \{\tilde{\mu}_2 - \tilde{\omega}_2\}}{n_I} \quad \text{in region 2,} \quad (18)$$

$$0 \leq \inf \{\tilde{\mu}_2 - \tilde{\omega}_2\} \quad \text{in region 3,} \quad (19)$$

$$P_F \leq P + \frac{\inf \{\tilde{\mu}_2 - \tilde{\omega}_2\}}{n_P} \quad \text{in region 4.} \quad (20)$$

**Theorem 2.** Let  $(\xi_1, \xi_2)$  belong to the region (10), (11), (12), so there exists a unique quasi-equilibrium. It is an equilibrium if and only if  $\tilde{\mu}_2 - \tilde{\omega}_2$  satisfies an additional condition, namely:

$$\inf \{\tilde{\mu}_2 - \tilde{\omega}_2\} \geq \frac{n_P(m + n_I)(\xi_2 - mP) + mn_I(\xi_2 - \xi_1)}{n_P(m + n_I)\rho + m(m + (1 + \rho)n_I)} \quad \text{in region 1;}$$

$$\inf \{\tilde{\mu}_2 - \tilde{\omega}_2\} \geq \frac{n_I(\xi_2 - \xi_1)}{m + (1 + \rho)n_I} \quad \text{in region 2;}$$

$$\inf \{\tilde{\mu}_2 - \tilde{\omega}_2\} \geq 0 \quad \text{in region 3;}$$

$$\inf \{\tilde{\mu}_2 - \tilde{\omega}_2\} \geq -\frac{mn_P(P - \frac{\xi_2}{m})}{m + \rho n_P} \quad \text{in region 4.}$$

*Proof.* The proof for region 1 comes from applying  $F$  on equation (17). For region 2, a direct application of  $F$  shows that equation (18) implies

$$\xi_2 - \xi_1 \leq \frac{m + (1 + \rho)n_I}{n_I} \inf \{\tilde{\mu}_2 - \tilde{\omega}_2\},$$

which must be read directly as a restriction on  $\inf \{\tilde{\mu}_2 - \tilde{\omega}_2\}$  given  $\xi_2$ . For region 3, the theorem is directly derived from equation (16), since  $X^* = 0$  and  $Y^* = 0$ . For region 4, a direct application of  $F$  shows that equation (20) gives the condition. Note that  $\inf \{\tilde{\mu}_2 - \tilde{\omega}_2\} \geq 0$  is a sufficient condition for an equilibrium to exist in region 4.  $\square$



Remark that the condition for region 1 is general in the following sense. Take  $n_P = 0$ , you get the condition for region 2; take  $n_I = 0$ , you get the condition for region 4; take now  $n_I = n_P = 0$ , you get the condition for region 3. This simple shortcut works for other analytical results. The explicit expressions of the prices, for each region, is given in Appendix.

## 5 Equilibrium analysis

In this section we analyze the equilibrium in two steps. Firstly, we examine the four regimes depicted in Figure 1. They correspond to very different types of decisions undertaken in the physical and the financial markets. Secondly, we turn to Figure 2 and enrich the discussion with the analysis of the net scarcity of the commodity, both immediate and expected.

### 5.1 Prices, physical and financial positions

A first general comment on Figure 1 is that in regimes 1 and 2 where  $X^* > 0$ , the futures market is in contango:  $P_F > P_1$ . Inventories are positive and they can be used for intertemporal arbitrages. In regimes 3 and 4, there is no inventory ( $X^* = 0$ ) and the market is in backwardation:  $P_F < P_1$ . These configurations are fully consistent with the theory of storage. The other meaningful comparison concerns  $P_F$  and  $E[\tilde{P}_2]$ . From Equation (9), we know that  $n_I X^* - n_P Y^*$  gives the sign and magnitude of  $E[\tilde{P}_2] - P_F$ , i.e. the way risk is transferred between the operators on the futures market.

The analysis of the four possible regimes, with a focus on regime 1 (it is the only one where all operators are active and it gathers two important subcases), enables us to unfold the reasons for the classical conjecture: backwardation on the expected basis, i.e.  $P_F < E[\tilde{P}_2]$ . More interestingly, we show why the reverse inequality is also plausible, as mentioned by several empirical studies.<sup>2</sup>

The equation  $n_I X^* - n_P Y^* = 0$  cuts regime 1 into two parts, 1U and 1L. It passes through  $M$  as can be seen in Figure 3. This frontier can be rewritten as:

$$\Delta : \quad P_F = \frac{n_I}{n_I + n_P} P_1 + \frac{n_P}{n_I + n_P} P. \quad (21)$$

- Along the line  $\Delta$ , there is no bias in the futures price, and the risk remains entirely in the hands of the hedgers (storers and producers have perfectly matching positions).
- Above  $\Delta$ ,  $n_I X^* > n_P Y^*$  and  $P_F < E[\tilde{P}_2]$ . This concerns the upper part of regime 1 (regime 1U) and regime 2.
- Below  $\Delta$ ,  $n_I X^* < n_P Y^*$  and  $P_F > E[\tilde{P}_2]$ . This concerns the lower part of regime 1 (regime 1L) and regime 4.

When  $n_I X^* > n_P Y^*$ , the net hedging position is short and speculators in long position are indispensable to the clearing of the futures market. In order to induce their participation,

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<sup>2</sup>For extensive analyses of the bias in a large number of commodity markets, see for example [Fama and French \(1987\)](#), [Kat and Oomen \(2006\)](#) and [Gorton et al. \(2012\)](#).

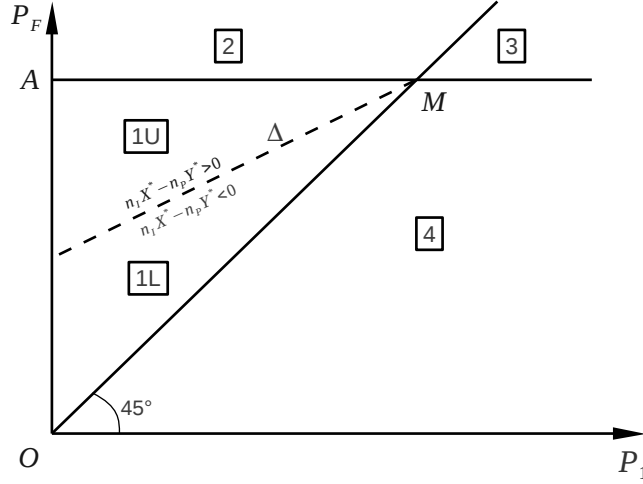


Figure 3: Phase diagram of physical and financial decisions in space  $(P_1, P_F)$  (zoom on Regime 1).

there must be a profitable bias between the futures price and the expected spot price: the bias  $E[\tilde{P}_2] - P_F$  is positive. This backwardation on the expected basis corresponds to the situation depicted by Keynes (1930) as the normal backwardation theory. On the contrary, when  $n_I X^* < n_P Y^*$ , the net hedging position is necessarily long and the speculators must be short. The expected spot price must be lower than the futures price, and the bias  $E[\tilde{P}_2] - P_F$  is negative.

Table 1 summarizes for each regime the relationships between the prices and the physical and financial positions. An attentive scrutiny of the table shows that the regimes are very contrasted.

For example, in regime 2, we have simultaneously a contango on the current basis and a backwardation on the expected basis (or a positive bias). In short,  $P_1 < P_F < E[\tilde{P}_2]$ . In regime 3, in the absence of hedging of any sort, the futures market is dormant, and this is no bias on the expected basis. Regime 4 is the opposite of regime 2: the market is in backwardation and, as  $X^* = 0$ , the net hedging position is long, the net speculative position is short and the bias is negative. In short,  $P_1 > P_F > E[\tilde{P}_2]$ .

## 5.2 Supply shocks

To exploit usefully Figure 2, one must bear in mind that the horizontal and vertical variables measure scarcity, not abundance:  $\xi_1 = \mu_1 - \omega_1$  is the extent to which current production  $\omega_1$  fails short of the demand of spot traders, and  $\xi_2 = E[\tilde{\mu}_2 - \tilde{\omega}_2]$  is the (expected) extent to which future production falls short of the demand of spot traders.

Assume that no markets are open before  $\xi_1$  is realized and assume that  $\xi_1$  brings no news (or revision) about  $\xi_2$ . We can fix  $\xi_2$ , and see what happens on equilibrium variables, depending on  $\xi_1$ . To fix ideas suppose that the expected situation at date 2 is a moderate scarcity, situated at  $\xi_2 = \bar{\xi}_2$ . The level of  $\bar{\xi}_2$  is common knowledge for the operators. Take it as drawn in Figure 4. In the case of a low  $\xi_1$  (abundance in period 1), we are in regime

1U	$P_1 < P_F$	$P_F < E[\tilde{P}_2]$	$P_F < P$
	$X^* > 0$	$f_S > 0$	$Y^* > 0$
$\Delta$	$P_1 < P_F$	$P_F = E[\tilde{P}_2]$	$P_F < P$
	$X^* > 0$	$f_S = 0$	$Y^* > 0$
1L	$P_1 < P_F$	$P_F > E[\tilde{P}_2]$	$P_F < P$
	$X^* > 0$	$f_S < 0$	$Y^* > 0$
2	$P_1 < P_F$	$P_F < E[\tilde{P}_2]$	$P_F > P$
	$X^* > 0$	$f_S > 0$	$Y^* = 0$
3	$P_1 > P_F$	$P_F = E[\tilde{P}_2]$	$P_F > P$
	$X^* = 0$	$f_S = 0$	$Y^* = 0$
4	$P_1 > P_F$	$P_F > E[\tilde{P}_2]$	$P_F < P$
	$X^* = 0$	$f_S < 0$	$Y^* > 0$

Table 1: Relationships between prices, physical and financial positions.

1U. If  $\xi_1$  is bigger, we are in regime 1L, and if  $\xi_1$  is even bigger, the equilibrium is in regime 4.

The interpretation is straightforward. If period 1 experiences abundance (regime 1U), there is massive storage (the current price is low and expected profits are attractive, since a future scarcity is expected). Storers need more hedging than processors, first because inventories are high, second because the expected release of stocks reduces the needs of the processors. Thus, there is a positive bias in the futures price and speculators have a buy position. For a less marked abundance (regime 1L), storage is more limited. The hedging needs of the storers diminishes while those of the processors increase. So the net hedging position is long, the bias in the futures price becomes negative and the speculators have a sell position. If the commodity is even scarcer (regime 4), there is no storage, only the processors are active and they hedge their positions.

The combination of the exogenous variables of the model (i.e. current or expected scarcity) with the activities on the physical market makes it possible to create a link between the storage and the normal backwardation theories. For example, it explains why, when there is a contango on the current basis in regime 1, we can have either an expected backwardation or an expected contango.

## 6 Welfare analysis

In this section, we shall express the indirect utilities of the various agents in equilibrium, and compute their sensitivities with respect to the parameters. We proceed in two steps. First, we compute the indirect utilities of the agents in equilibrium, as functions of equilibrium prices  $P_1$  and  $P_F$ . Second, we compute the elasticities of  $P_1$  and  $P_F$  to deduce the elasticities of the indirect utilities. We restrict ourselves to the richer case, *i.e.* Regime 1, where all agents are active. Recall that then we have:

$$P_F < P \text{ and } P_1 < P_F; \quad (22)$$

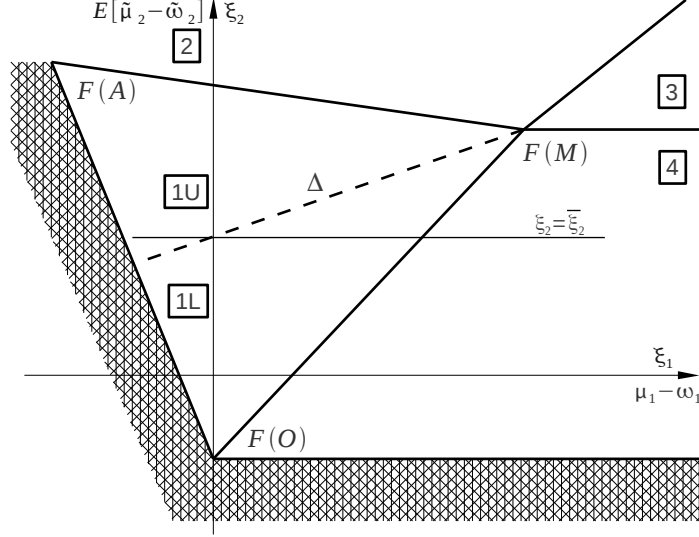


Figure 4: Phase diagram of physical and financial decisions in space (zoom on Regime 1).

$$\tilde{P}_2 = \frac{1}{m} (\tilde{\mu}_2 - \tilde{\omega}_2 - n_I (P_F - P_1) + n_P (P - P_F)); \quad (23)$$

$$mP_1 - n_I (P_F - P_1) = \xi_1; \quad (24)$$

$$mP_F + \rho (n_I (P_F - P_1) - n_P (P - P_F)) = \xi_2. \quad (25)$$

As above, we shall set  $\xi_2 := E[\tilde{\mu}_2 - \tilde{\omega}_2]$  and  $\xi_1 := \mu_1 - \omega_1$ .

## 6.1 Indirect utilities

The indirect utility of the speculators is given by:

$$U_S = f_S^* (E[\tilde{P}_2] - P_F) - \frac{1}{2} \alpha_S f_S^{*2} \text{Var}[\tilde{P}_2],$$

where we have to substitute the value of  $f_S^*$ , which leads to:

$$U_S = \frac{(E[\tilde{P}_2] - P_F)^2}{2\alpha_S \text{Var}[\tilde{P}_2]}. \quad (26)$$

Let us now turn to the storers. Their indirect utility is given by:

$$U_I = (x^* + f_I^*) E[\tilde{P}_2] - x^* P_1 - f_I^* P_F - \frac{1}{2} C x^{*2} - \frac{1}{2} \alpha_I (x + f_I^*)^2 \text{Var}[\tilde{P}_2],$$

where we substitute the values of  $f_I^*$ ,  $x^*$  and  $y^*$ :

$$U_I = \frac{(E[\tilde{P}_2] - P_F)^2}{2\alpha_I \text{Var}[\tilde{P}_2]} + \frac{(P_F - P_1)^2}{2C}. \quad (27)$$

For the processors we have, in a similar fashion:

$$U_P = \frac{(E[\tilde{P}_2] - P_F)^2}{2\alpha_P \text{Var}[\tilde{P}_2]} + \frac{(P_F - P)^2}{2\beta P}. \quad (28)$$

We thus obtain, for all categories of agents, a clear separation between two additive components of the indirect utilities. The first is associated with the level of the expected basis and is clearly linked with speculation. The second is associated with the level of the current basis or the futures prices and is linked with the hedged activity on the physical market. We shall name  $U_{S_i}$  this first component for the category of agent  $i$ , and  $U_{H_i}$  the second one.

Quite intuitively, for all operators,  $U_{S_i}$  is all the more important as the futures market is biased, whatever the sign of the bias; it decreases with respect to risk aversion and to the variance of the expected spot price.  $U_{H_i}$  changes with the category of agent under consideration. For the storers, it is positively correlated to the current basis and diminishes with storage costs. For the processors, it rises with the margin on the processing activity and decreases with the production costs.

We will now particularize formulas (26), (27) and (28) to the case when the markets are in equilibrium. In that case,  $\tilde{P}_2$  becomes a function of  $(P_1, P_F)$ , and the formulas become (after replacing the  $n_i$  by their values in terms of the  $N_i$ ):

$$U_S = \frac{\text{Var}[\tilde{\xi}_2]}{2\alpha_S \left(\sum \frac{N_i}{\alpha_i}\right)^2} \left( \frac{N_I}{C} (P_F - P_1) - \frac{N_P}{\beta P} (P - P_F) \right)^2; \quad (29)$$

$$U_I = \frac{\text{Var}[\tilde{\xi}_2]}{2\alpha_I \left(\sum \frac{N_i}{\alpha_i}\right)^2} \left( \frac{N_I}{C} (P_F - P_1) - \frac{N_P}{\beta P} (P - P_F) \right)^2 + \frac{(P_F - P_1)^2}{2C}; \quad (30)$$

$$U_P = \frac{\text{Var}[\tilde{\xi}_2]}{2\alpha_S \left(\sum \frac{N_i}{\alpha_i}\right)^2} \left( \frac{N_I}{C} (P_F - P_1) - \frac{N_P}{\beta P} (P - P_F) \right)^2 + \frac{(P_F - P)^2}{2\beta P}. \quad (31)$$

Note for future use that these are indirect utilities *per head*: for instance, there are  $N_I$  storers, they are all identical, and  $U_I$  is the indirect utility of each one of them. This will enable us to do a welfare analysis in the next subsection.

## 6.2 The impact of speculators on the welfare of others

Formulas (29), (30) and (31) give us the indirect utilities of the agents at equilibrium in terms of the equilibrium prices  $P_1$  and  $P_F$ . These can in turn be expressed in terms of the fundamentals of the economy, namely  $\xi_1$  and  $\tilde{\xi}_2$  (see Appendix A): substituting formulas (45), (46) and (47), we get new expressions, which can be differentiated to give the sensitivities of the indirect utilities with respect to the parameters in the model.

However, it is better to work directly with formulas (29), (30) and (31). We will then need the sensitivities of  $P_1$  and  $P_F$  with respect to the varying parameter, but these can be derived from the system (24)-(25) by the implicit function theorem. To see how it is done, let us compute the sensitivities with respect to  $N_S$ , the number of speculators. In other words, we will investigate whether an increase in the number of speculators increases or decreases the welfare of speculators, of inventory holders, and of industry processors.

**Sensitivities of prices** We first compute the sensitivities  $\frac{dP_1}{dN_S}$  and  $\frac{dP_F}{dN_S}$ . We get them by differentiating (24)-(25):

$$\begin{aligned} m \frac{dP_1}{dN_S} - n_I \left( \frac{dP_F}{dN_S} - \frac{dP_1}{dN_S} \right) &= 0, \\ m \frac{dP_F}{dN_S} + \rho \left( n_I \left( \frac{dP_F}{dN_S} - \frac{dP_1}{dN_S} \right) + n_P \frac{dP_F}{dN_S} \right) &= -\frac{d\rho}{dN_S} (n_I (P_F - P_1) - n_P (P - P_F)), \end{aligned}$$

which yields:

$$\frac{dP_F}{dN_S} = \left( \frac{m}{n_I} + 1 \right) \frac{dP_1}{dN_S}, \quad (32)$$

$$\begin{aligned} \frac{dP_1}{dN_S} &= \frac{d\rho}{dN_S} \frac{n_P (P - P_F) - n_I (P_F - P_1)}{\left( \frac{m}{n_I} + 1 \right) (m + \rho n_P) - \rho m} \\ &= -\frac{m}{\alpha_S} \frac{\text{Var}[\tilde{\xi}_2] n_P (P - P_F) - n_I (P_F - P_1)}{\left( \sum \frac{N_i}{\alpha_i} \right)^2 \left( \frac{m}{n_I} + 1 \right) (m + \rho n_P) + \rho m}. \end{aligned} \quad (33)$$

**Sensitivity of  $U_S$**  Differentiating formula (29) yields:

$$\begin{aligned} \frac{dU_S}{dN_S} &= \frac{\text{Var}[\tilde{\xi}_2]}{\alpha_S \left( \sum \frac{N_i}{\alpha_i} \right)^2} (n_I (P_F - P_1) - n_P (P - P_F)) \left( m + n_P \left( 1 + \frac{m}{n_I} \right) \right) \frac{dP_1}{dN_S} \\ &\quad - \frac{\text{Var}[\tilde{\xi}_2]}{\alpha_S^2 \left( \sum \frac{N_i}{\alpha_i} \right)^3} (n_I (P_F - P_1) - n_P (P - P_F))^2 \\ &= -\frac{\text{Var}[\tilde{\xi}_2]}{\alpha_S^2 \left( \sum \frac{N_i}{\alpha_i} \right)^3} \left( \frac{\text{Var}[\tilde{\xi}_2] m \left( m + n_P \left( 1 + \frac{m}{n_I} \right) \right)}{\sum \frac{N_i}{\alpha_i} \left( \frac{m}{n_I} + 1 \right) (m + \rho n_P) + \rho m} + 1 \right) \\ &\quad \times (n_I (P_F - P_1) - n_P (P - P_F))^2. \end{aligned} \quad (34)$$

The sign of  $\frac{dU_S}{dN_S}$  is constant in region 1: it is negative. Adding speculators decreases the remuneration associated to risk bearing.

**Sensitivity of  $U_I$**  Differentiating formula (30) yields:

$$\begin{aligned} \frac{dU_I}{dN_S} &= \frac{dU_S}{dN_S} + \frac{P_F - P_1}{C} \left( \frac{dP_F}{dN_S} - \frac{dP_1}{dN_S} \right) \\ &= -\frac{\text{Var}[\tilde{\xi}_2]}{\alpha_S^2 \left( \sum \frac{N_i}{\alpha_i} \right)^3} \left( \frac{\text{Var}[\tilde{\xi}_2] m \left( m + n_P \left( 1 + \frac{m}{n_I} \right) \right)}{\sum \frac{N_i}{\alpha_i} \left( \frac{m}{n_I} + 1 \right) (m + \rho n_P) + \rho m} + 1 \right) \\ &\quad \times (n_I (P_F - P_1) - n_P (P - P_F))^2 \\ &\quad - \frac{P_F - P_1}{C} \frac{m}{n_I} \frac{m}{\alpha_S} \frac{\text{Var}[\tilde{\xi}_2]}{\left( \sum \frac{N_i}{\alpha_i} \right)^2} \frac{n_I (P_F - P_1) - n_P (P - P_F)}{\left( \frac{m}{n_I} + 1 \right) (m + \rho n_P) + \rho m}. \end{aligned} \quad (35)$$

As mentioned before, the utility due to speculative activities decreases when  $N_S$  increases. As far as the utility of hedging is concerned, the effect depends on the sign of:  $n_I(P_F - P_1) - n_P(P - P_F)$ . Remind that this line separates Region 1 into two subregions. In Region 1U, the utility of hedging increases for the storers, because they need more hedging than processors. The opposite conclusion arises in Region 1L.

As far as the total utility is concerned, we will not pursue the calculations further, noting simply that  $(n_I(P_F - P_1) - n_P(P - P_F))$  factors, so that the result is of the form:

$$\frac{dU_I}{dN_S} = A(n_I(P_F - P_1) - n_P(P - P_F))(K_1(P_F - P_1) + K_2(P - P_F)),$$

for suitable constants  $A$ ,  $K_1$ , and  $K_2$ . This means that the sign changes across

- the line  $\Delta$ , already encountered, defined by  $n_I(P_F - P_1) + n_P(P - P_F) = 0$ ;
- the line  $D$ , defined by the equation  $K_1(P_F - P_1) + K_2(P - P_F) = 0$ .

Both  $\Delta$  and  $D$  go through the point  $M$  where  $P_1 = P_F = P$ . If  $K_2/K_1 < 0$ , the line  $D$  enters region 1, if  $K_2/K_1 > 0$ , it does not. So, if  $K_2/K_1 > 0$ , region 1 is divided in three subregions by the lines  $D$  and  $\Delta$ , and the sign changes when one crosses from one to the other. If  $K_2/K_1 < 0$ , region 1 is divided in two subregions by the line  $\Delta$ , and the sign changes across  $\Delta$ . In all cases, the response of inventory holders to an increase in the number of speculators will depend on the equilibrium.

**Sensitivity of  $U_P$**  Differentiating formula (31) yields:

$$\begin{aligned} \frac{dU_P}{dN_S} &= \frac{dU_S}{dN_S} + \frac{P_F - P}{\beta P} \frac{dP_F}{dN_S} \\ &= - \frac{\text{Var}[\tilde{\xi}_2]}{\alpha_S^2 \left(\sum \frac{N_i}{\alpha_i}\right)^3} \left( \frac{\text{Var}[\tilde{\xi}_2]}{\sum \frac{N_i}{\alpha_i}} \frac{m \left(m + n_P \left(1 + \frac{m}{n_I}\right)\right)}{\left(\frac{m}{n_I} + 1\right) (m + \rho n_P) + \rho m} + 1 \right) \\ &\quad \times (n_I(P_F - P_1) - n_P(P - P_F))^2 \\ &\quad - \frac{P_F - P}{\beta P} \left(\frac{m + n_I}{n_I}\right) \frac{m}{\alpha_S} \frac{\text{Var}[\tilde{\xi}_2]}{\left(\sum \frac{N_i}{\alpha_i}\right)^2} \frac{n_I(P_F - P_1) - n_P(P - P_F)}{\left(\frac{m}{n_I} + 1\right) (m + \rho n_P) + \rho m}. \end{aligned} \quad (36)$$

Again, the utility due to speculation decreases and that linked with hedging depends on the sign of:  $n_I(P_F - P_1) - n_P(P - P_F)$ . In Region 1U, the utility of hedging decreases for the processors, and it increases in Region 1L.

We will not pursue the calculations further, noting simply that  $n_I(P_F - P_1) - n_P(P - P_F)$  factors again, so that:

$$\frac{dU_P}{dN_S} = A^*(n_I(P_F - P_1) - n_P(P - P_F))(K_1^*(P_F - P_1) + K_2^*(P - P_F))$$

As in the preceding case, there will be a line  $D^*$  (different from  $D$ ), which enters region 1 if  $K_1^*/K_2^* < 0$  and does not if  $K_1^*/K_2^* > 0$ . In the first case, region 1 is divided into three subregions by  $D$  and  $\Delta^*$ , in the second it is divided into two subregions by  $\Delta$ , and the sign of  $\frac{dU_I}{dN_P}$  changes when one crosses the frontiers.



**Speculation and welfare in summary** Remind that all agents are speculators in their ways. This activity gives the sign of the first term of the derivative of welfare with respect to  $N_S$  (the speculation term): if the speculators lose from being more, then all agents lose as far as only speculation is concerned. This said, remark that the second term in the derivative of welfare concerns only the storers and the processors (the hedging term). They go in opposite direction in regime 1: in subcase 1U, if the number of speculators increases, the hedging term is positive for storers and negative for processors. It is the other way around in subcase 1L.

In terms of political economy (in the sense that economic interests may determine political positions), we can simplify the message as follows. Note that in the neighborhood of  $\Delta$ , the speculation term is of second order with respect to the hedging term. Therefore, the interests of storers and processors are systematically opposed. Storers are in favor of (processors are against) an increase in the number of speculators if they demand more futures (in absolute value) than processors can offer (subcase 1U). The opposite positions are taken if processors are demanding more futures in absolute value (subcase 1L).

### 6.3 The impact of speculators on prices

The best is to focus on regimes 2 and 4 first, in order to examine simple mechanisms, then discuss regime 1, in which the previous effects are mixed in interesting ways. The equations are drawn from the Appendix A.

Up to now, the analysis has assumed that  $\xi_1$  is known when markets open and that prices are determined. In what follows we keep this view and we complete it by considering prices too as random variables at a previous stage. In such a case,  $\xi_1$  becomes random. More precisely,  $\xi_1$  and  $\tilde{\xi}_2$  are random, while  $\xi_2 = E[\tilde{\xi}_2]$  is a number.

This leads us to distinguish conditional and unconditional expectations and variances, i.e.  $E[\cdot | \xi_1]$  and  $E[\cdot]$  on the one hand, and  $\text{Var}[\cdot | \xi_1]$  and  $\text{Var}[\cdot]$  on the other. Finally, we assume that  $\xi_1$  and  $\tilde{\xi}_2$  are independent.

**Regime 2** The equilibrium is such that:

$$P_1 = \frac{(m + n_I \rho) \frac{\xi_1}{m} + n_I \frac{\xi_2}{m}}{m + n_I(1 + \rho)}; P_F = \frac{n_I \rho \frac{\xi_1}{m} + (m + n_I) \frac{\xi_2}{m}}{m + n_I(1 + \rho)}; \tilde{P}_2 = \frac{\tilde{\xi}_2}{m} - \frac{n_I \left( \frac{\xi_2}{m} - \frac{\xi_1}{m} \right)}{m + n_I(1 + \rho)};$$

$$X^* = \frac{m \left( \frac{\xi_2}{m} - \frac{\xi_1}{m} \right)}{m + n_I(1 + \rho)}; Y^* = 0.$$

The fact that  $P_1$  and  $P_F$  are weighted averages of  $\xi_1/m$  and  $\xi_2/m$ , and the fact that  $\frac{\xi_2}{m} \geq \frac{\xi_1}{m}$  in regime 2, determine the comparative statics.

Note in particular that:

$$\text{Var}[\tilde{P}_2] = \frac{\text{Var}[\tilde{\xi}_2]}{m^2} + \left( \frac{n_I}{m + n_I(1 + \rho)} \right)^2 \text{Var}[\xi_1].$$

Increasing the number of speculators  $N_S$ :

- increases  $P_1$  and  $E[P_1]$ ; decreases  $\text{Var}[P_1]$ ;
- increases  $P_F$  and decreases  $\text{Var}[P_F]$ ;
- decreases  $\tilde{P}_2$ ,  $E[\tilde{P}_2 | \xi_1]$  and  $E[\tilde{P}_2]$ ; doesn't change  $\text{Var}[\tilde{P}_2 | \xi_1]$  and increases  $\text{Var}[\tilde{P}_2]$ .

An interesting summary of these effects can be found in the analysis of the bases. Remark first that the expected basis is:

$$E[\tilde{P}_2] - P_F = \frac{n_I(\rho - 1) \left( \frac{\xi_2}{m} - \frac{\xi_1}{m} \right)}{m + n_I(1 + \rho)} \geq 0.$$

Increasing  $N_S$  decreases  $E[\tilde{P}_2] - P_F$ . The buying positions of the speculators, motivated by the presence of a positive premium, increase. Thus there is a rise in the futures prices, the cost of hedging diminishes for storers, and this has an impact on the physical market. More precisely, the current basis increases. Indeed:

$$P_F - P_1 = \frac{\xi_2 - \xi_1}{m + n_I(1 + \rho)}$$

As it becomes more profitable, storage increases. More storage for a given shock in period 1 means that cash-and-carry strategies are enhanced. A price increase results from the building of inventories, and this price exhibits less variance because of these supplementary stocks. The latter are released in period 2, which explains the lower spot price and the higher variance (remind that  $\xi_1$  and  $\tilde{\xi}_2$  are independent).

**Regime 4** The equilibrium is such that:

$$P_1 = \frac{\xi_1}{m}; P_F = \frac{m \frac{\xi_2}{m} + n_P \rho P}{m + n_P \rho}; \tilde{P}_2 = \frac{\tilde{\xi}_2}{m} + \frac{n_P (P - \frac{\xi_2}{m})}{m + n_P \rho};$$

$$X^* = 0; Y^* = \frac{m (P - \frac{\xi_2}{m})}{m + n_P \rho}.$$

Again,  $P_1$  and  $P_F$  are weighted averages of  $\xi_1/m$  and  $\xi_2/m$ . This, in addition to the fact that  $\frac{\xi_2}{m} \leq P$  in regime 4, determine the comparative statics.

Note in particular that:

$$\text{Var}[\tilde{P}_2 | \xi_1] = \text{Var}[\tilde{P}_2] = \frac{\text{Var}[\tilde{\xi}_2]}{m^2}.$$

Increasing the number of speculators  $N_S$ :

- doesn't change  $P_1$  and  $\text{Var}[P_1]$ ;
- decreases  $P_F$ ;
- increases  $\tilde{P}_2$ ,  $E[\tilde{P}_2 | \xi_1]$  and  $E[\tilde{P}_2]$ ; doesn't change  $\text{Var}[\tilde{P}_2 | \xi_1]$  and  $\text{Var}[\tilde{P}_2]$ .

There is no storage and thus no physical impact of futures and speculators in the first period; this explains why  $P_1$  is unchanged. Concerning the other variables, remark that:

$$P_F - E[\tilde{P}_2] = \frac{n_P(\rho - 1) \left(P - \frac{\xi_2}{m}\right)}{m + n_P\rho} \geq 0.$$

When the number of speculators rises, processors benefit from better hedging conditions:  $P_F - E[\tilde{P}_2]$  decreases. This implies in turn that overall physical demand in the second period increases, hence the effects on  $\tilde{P}_2$  and its moments.

**Regime 1** 1U and 1L appear as the relevant sub-regimes, the former resembling regime 2 and the latter resembling regime 4, with simple and interpretable differences.

The equilibrium is such that:

$$P_1 = \frac{(m + (n_I + n_P)\rho)\frac{\xi_1}{m} + n_I\frac{\xi_2}{m} + n_I n_P \rho m^{-1} P}{m + (n_I + n_P)\rho + n_I + n_I n_P \rho m^{-1}} \quad (37)$$

$$P_F = \frac{n_I \rho \frac{\xi_1}{m} + (m + n_I)\frac{\xi_2}{m} + (m + n_I)n_P \rho m^{-1} P}{n_I \rho + (m + n_I) + (m + n_I)n_P \rho m^{-1}} \quad (38)$$

$$\tilde{P}_2 = \frac{\tilde{\xi}_2}{m} + \frac{n_I \frac{\xi_1}{m} - ((m + n_I)n_P m^{-1} + n_I)\frac{\xi_2}{m} + (m + n_I)n_P m^{-1} P}{n_I \rho + (m + n_I) + (m + n_I)n_P \rho m^{-1}} \quad (39)$$

$$X^* = \frac{-(m + n_P\rho)\frac{\xi_1}{m} + m\frac{\xi_2}{m} + n_P \rho P}{n_I \rho + (m + n_I) + (m + n_I)n_P \rho m^{-1}} \quad (40)$$

$$Y^* = \frac{-n_I \rho \frac{\xi_1}{m} - (m + n_I)\frac{\xi_2}{m} + (m + (1 + \rho)n_I)P}{n_I \rho + (m + n_I) + (m + n_I)n_P \rho m^{-1}}. \quad (41)$$

Prices have the form  $\frac{A+B\rho}{C+D\rho}$ , with positive numerators and denominators. Such expressions are increasing with respect to  $\rho$  if  $BC - DA \geq 0$ . This is how most comparative statics are calculated what follows.

First, remark that  $P_1$  increases with respect to  $\rho$  if:

$$n_I \left(\frac{\xi_1}{m} - \frac{\xi_2}{m}\right) + \left(1 + \frac{n_I}{m}\right) n_P \left(P - \frac{\xi_2}{m}\right) \geq 0.$$

Moreover, the variances of the prices (conditional and unconditional) are:

$$\begin{aligned} \text{Var}[P_1] &= \text{Var} \left[ \frac{(m + (n_I + n_P)\rho)\frac{\xi_1}{m}}{m + (n_I + n_P)\rho + n_I + \frac{n_I n_P}{m}\rho} \right] \\ &= \left( \frac{m + (n_I + n_P)\rho}{m + (n_I + n_P)\rho + n_I + \frac{n_I n_P}{m}\rho} \right)^2 \frac{\text{Var}[\tilde{\xi}_1]}{m^2}. \end{aligned} \quad (42)$$

$$\text{Var}[\tilde{P}_2 \mid \xi_1] = \frac{\text{Var}[\tilde{\xi}_2]}{m^2}, \quad (43)$$

$$\text{Var}[\tilde{P}_2] = \left( \frac{n_I}{(n_I + n_P + \frac{1}{m}n_I n_P)\rho + (m + n_I)} \right)^2 \frac{\text{Var}[\xi_1]}{m^2} + \frac{\text{Var}[\tilde{\xi}_2]}{m^2}. \quad (44)$$

To summarize, we can see that in regime 1U, increasing the number of speculators  $N_S$  :

- increases  $P_1$  and decreases  $\text{Var}[P_1]$ ;
- increases  $P_F$ ;
- decreases  $\tilde{P}_2$  and  $E[\tilde{P}_2 \mid \xi_1]$ ;
- doesn't change  $\text{Var}[\tilde{P}_2 \mid \xi_1]$  and increases  $\text{Var}[\tilde{P}_2]$ ;
- increases  $X^*$  and decreases  $Y^*$ .

Increasing  $N_S$  in regime 1L:

- decreases  $P_1$  and  $\text{Var}[P_1]$ ;
- decreases  $P_F$ ;
- increases  $\tilde{P}_2$  and  $E[\tilde{P}_2 \mid \xi_1]$ ;
- doesn't change  $\text{Var}[\tilde{P}_2 \mid \xi_1]$  and increases  $\text{Var}[\tilde{P}_2]$ ;
- decreases  $X^*$  and increases  $Y^*$ .

We can now examine the effects on quantities.

Examining how storage  $X^*$  changes when  $\rho$  increases amounts to examining  $P_F - P_1$ :

$$P_F - P_1 = \frac{(m + n_P \rho) \left( \frac{\xi_2}{m} - \frac{\xi_1}{m} \right) + n_P \rho \left( P - \frac{\xi_2}{m} \right)}{m + n_I + \left( n_I + n_P + \frac{n_I n_P}{m} \right) \rho},$$

This moves like  $P_1$  (more storage means more demand in the first period).

The analysis  $Y^*$ , i.e. of  $P - P_F$ , is straightforward, since  $P$  is a constant.

Finally, remark that the bias:

$$P_F - E[\tilde{P}_2] = \frac{(\rho - 1) \left( n_I \left( \frac{\xi_1}{m} - \frac{\xi_2}{m} \right) + \left( 1 + \frac{n_I}{m} \right) n_P \left( P - \frac{\xi_2}{m} \right) \right)}{m + n_I + \left( n_I + n_P + \frac{n_I n_P}{m} \right) \rho}$$

is also easily analyzed : when this bias is positive (negative), which is the case in regime 1L (1U), an increase in the number of the speculators diminishes the hedging costs of the processors (storsers) and rises that of the storsers (processors).

To summarize, the results obtained in regime 1 are similar to those found in more simple cases (regimes 2 and 4 respectively). However, remark that in regime 1L,  $P_1$  decreases, whereas it is constant in Regime 4. This is due to the fact that the storsers, are facing an increase in their hedging costs.

The conclusions reached towards the analysis of the impact of speculators on prices is at least partly, consistent with what was found on welfare. An increasing number of speculators can have a positive or a negative impact for the hedgers, according to the regime or sub-regime under consideration. This, in turn, affects the inventories and thus the level of the spot price at periods 1 and 2. In the end, everything depends on which side of the hedging demand dominates. Note also that Appendix C completes this analysis with comparisons between the basic scenario and another in which the futures market is closed.

## 7 Conclusion

Our model, although extremely simple, perhaps the simplest possible, which allows the interaction between a physical spot market and a financial futures market, exhibits a surprising variety of behaviors. In equilibrium, there may be a contango or a backwardation, the futures price may be higher or lower than the expected spot price, inventory holders may or may not hold inventory, industrial processors may or may not buy forward, adding speculators may increase or decrease the indirect hedging utilities of inventory holders and of industrial processors. All depends, in a way we determine, on market fundamentals and the realization of shocks in the physical market. This rich variety of behaviors can be found in commodities markets as they go, and we have not found in the literature a model which encompasses them all. While filling this gap, and to the best of our knowledge, the present paper offers, for the first time since 1930, a unified framework for the analysis of price relationships in commodity futures markets.

Of course, our model is too simple to capture some important effects; for instance, we would like to understand the so-called convenience yield, which is usually explained as the option value of holding stock. This cannot be understood within a two-period model. So developing a multi-period model, perhaps even an infinite-horizon one, is the next step in our approach. It would be interesting to see how the conclusions of the two-period model fare in the multi-period or the infinite-horizon model.

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## A Prices: explicit expressions

Note that  $\xi_1 := \mu_1 - \omega_1$ ,  $\tilde{\xi}_2 := \tilde{\mu}_2 - \tilde{\omega}_2$ ,  $\xi_2 := E[\tilde{\mu}_2 - \tilde{\omega}_2]$ ,  $n_I := N_I/C$  and  $n_P := \frac{N_P}{\beta P}$ .

$(\xi_1, \xi_2)$  determine the regime, and the final expressions of equilibrium prices are as follows.

**Regime 1** :

$$P_1 = \frac{(m + (n_I + n_P)\rho)\frac{\xi_1}{m} + n_I\frac{\xi_2}{m} + n_I n_P \rho m^{-1} P}{m + (n_I + n_P)\rho + n_I + n_I n_P \rho m^{-1}}, \quad (45)$$

$$P_F = \frac{n_I \rho \frac{\xi_1}{m} + (m + n_I)\frac{\xi_2}{m} + (m + n_I)n_P \rho m^{-1} P}{n_I \rho + (m + n_I) + (m + n_I)n_P \rho m^{-1}}, \quad (46)$$

$$\tilde{P}_2 = \frac{\tilde{\xi}_2}{m} + \frac{n_I \frac{\xi_1}{m} - ((m + n_I)n_P m^{-1} + n_I)\frac{\xi_2}{m} + (m + n_I)n_P m^{-1} P}{n_I \rho + (m + n_I) + (m + n_I)n_P \rho m^{-1}}, \quad (47)$$

$$X^* = \frac{-(m + n_P\rho)\frac{\xi_1}{m} + m\frac{\xi_2}{m} + n_P\rho P}{n_I\rho + (m + n_I) + (m + n_I)n_P\rho m^{-1}}, \quad (48)$$

$$Y^* = \frac{-n_I\rho\frac{\xi_1}{m} - (m + n_I)\frac{\xi_2}{m} + (m + (1 + \rho)n_I)P}{n_I\rho + (m + n_I) + (m + n_I)n_P\rho m^{-1}}. \quad (49)$$

Remark that all denominators are equal. They are written in different ways only to show that  $P_1$  and  $P_F$  are convex combinations of  $\frac{\xi_1}{m}$ ,  $\frac{\xi_2}{m}$  and  $P$ .

Note that starting from regime 1, setting  $n_I$  or  $n_P$  to 0 in the expressions to get the prices for any other region works perfectly. For example, the prices for regime 2 can be directly retrieved by posing  $n_P = 0$  in equations (45)-(49).

**Regime 2 :**

$$P_1 = \frac{(m + n_I\rho)\frac{\xi_1}{m} + n_I\frac{\xi_2}{m}}{m + n_I(1 + \rho)}; P_F = \frac{n_I\rho\frac{\xi_1}{m} + (m + n_I)\frac{\xi_2}{m}}{m + n_I(1 + \rho)}; \tilde{P}_2 = \frac{\tilde{\xi}_2}{m} + \frac{n_I(\frac{\xi_1}{m} - \frac{\xi_2}{m})}{m + n_I(1 + \rho)};$$

$$X^* = \frac{-m(\frac{\xi_1}{m} - \frac{\xi_2}{m})}{m + n_I(1 + \rho)}; Y^* = 0.$$

**Regime 3 :**

$$P_1 = \frac{\xi_1}{m}; P_F = \frac{\xi_2}{m}; \tilde{P}_2 = \frac{\tilde{\xi}_2}{m}; X^* = 0; Y^* = 0.$$

**Regime 4 :**

$$P_1 = \frac{\xi_1}{m}; P_F = \frac{m\frac{\xi_2}{m} + n_P\rho P}{m + n_P\rho}; \tilde{P}_2 = \frac{\tilde{\xi}_2}{m} + \frac{n_P(P - \frac{\xi_2}{m})}{m + n_P\rho};$$

$$X^* = 0; Y^* = \frac{m(P - \frac{\xi_2}{m})}{m + n_P\rho}.$$

## B Existence: qualitative comparative statics on the basic scenario

We show in this appendix that, for a given distribution of  $(\xi_1, \xi_2)$ , if risk or risk aversions increase, regime 1, in which all markets and all operators are active, becomes more likely.

Beside  $\mu_1 - \omega_1$  and  $E[\tilde{\mu}_2 - \tilde{\omega}_2]$ , the model parameters are  $\text{Var}[\tilde{\mu}_2 - \tilde{\omega}_2]$ , the forward price  $P$  at which the processor can sell his product, the numbers  $N_P, N_I$  and  $N_S$ , the risk aversion parameters  $\alpha_P, \alpha_I$  and  $\alpha_S$ , the production coefficient  $\beta$ , the cost of storage  $C$  and the elasticity of spot traders' demand  $m$ .

Before we proceed with the comparative statics, note that  $\text{Var}[\tilde{\mu}_2 - \tilde{\omega}_2]$  and  $\alpha_P, \alpha_I$  and  $\alpha_S$  appear only through the single parameter:

$$\rho = 1 + m \frac{\text{Var}[\tilde{\mu}_2 - \tilde{\omega}_2]}{\frac{N_P}{\alpha_P} + \frac{N_I}{\alpha_I} + \frac{N_S}{\alpha_S}}.$$



We will thus concentrate our attention on this parameter.

Of particular interest is the case  $\rho = 1$ . This happens when one of the following conditions is verified:

- $\text{Var}[\tilde{\mu}_2 - \tilde{\omega}_2] = 0$  (the future is deterministic and known);
- the agents are risk neutral (it is worth emphasizing that our model does not rely on risk aversion to function: even in the risk-neutral case, the four market configurations appear);
- at least one sector is extremely competitive  $N_i = +\infty$  for some  $i$ ;
- $m$ , the elasticity of the demand to the price is zero.

In all other cases,  $\rho$  is higher than 1. It increases with the elasticity of the demand, with the uncertainty on the future availability of the commodity, with risk aversion, and it diminishes with the number of operators.

In the case  $\rho = 1$ , we have:

$$\begin{aligned} F(O) &= (0, -n_P P), \\ F(A) &= P(-n_I, m + n_I), \\ F(M) &= mP(1, 1). \end{aligned}$$

and the upper boundary of region 3 has slope 1, so that region 3 has the minimum possible size. This means that the conditions are the most favorable to active physical markets.

Figure 5 illustrates what happens as  $\rho$  increases from 1 to  $+\infty$  due to a change of  $\text{Var}[\tilde{\mu}_2 - \tilde{\omega}_2]$  or of one of the  $\alpha_i$ . The point  $F(M)$  remains fixed, while  $F(O)$  and  $F(A)$  move vertically, the first one downwards and the second one upwards. So region 1 is enlarged, but the effects are ambiguous for region 4. Region 3 also enlarges, as the slope of the half-line emanating from  $F(M)$  increases towards the vertical. Region 2 is the only one to be unambiguously reduced.

## C Comparison with the no-futures scenario (NF)

When there is no futures markets (scenario NF), speculators are inactive. There remains only three kinds of operators: storers, processors, and spot traders.

In what follows, we can economize on calculations by applying the parameter transposition described by table 2 on the previous results. The validity of the method is formally established in the proof of Theorem 3.

Basic scenario:	$P_F$	$\rho$	$n_I$	$n_P$
NF scenario:	$E[\tilde{P}_2]$	1	$\underline{n}_I = n_I \times \frac{C}{C + \alpha_I V_2}$	$\underline{n}_P = n_P \times \frac{\beta}{\beta + \alpha_P \frac{V_2}{P}}$

Table 2: How to transpose the basic scenario's results to scenario NF.

The following notation will be used:  $V_2 := \text{Var}[\tilde{P}_2]$ , an exogenous parameter.

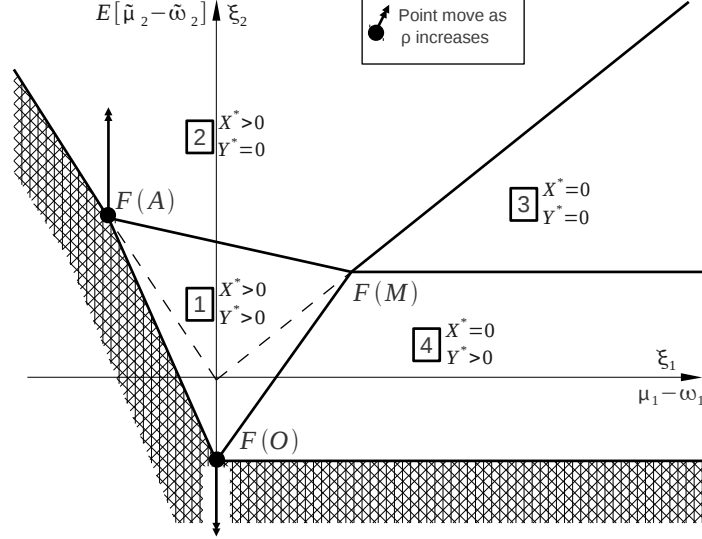


Figure 5: Phase diagram of physical and financial decisions (effect of  $\rho$ ).

The optimal position of the storer becomes:

$$\underline{x}^* = \frac{1}{C + \alpha_I V_2} \max\{E[\tilde{P}_2] - P_1, 0\}. \quad (50)$$

The storer holds inventory if the expected price is higher than the current spot price.

An easy computation gives the optimal decision of the processor, namely:

$$\underline{y}^* = \frac{1}{\beta P + \alpha_P V_2} \max\{P - E[\tilde{P}_2], 0\}. \quad (51)$$

Unless the forward price of the final product is higher than the expected spot price of the commodity, the processor has no activity.

**Theorem 3** (Existence conditions). *With the notation  $\xi_1 := \mu_1 - \omega_1$ ,  $\xi_2 := E[\tilde{\mu}_2 - \tilde{\omega}_2]$  and  $V_2 := \text{Var}[\tilde{\mu}_2 - \tilde{\omega}_2]$ , existence conditions on  $\xi_1$ ,  $\xi_2$  and  $V_2$  are stricter in scenario NF than in the basic case.*

*Region 1 in NF is included in basic region 1. Region 2 in NF gains on basic region 1 and is cut on its left border. Region 3 doesn't change. Region 4 in NF gains on basic region 1 and is cut on its bottom border.*

See Figure 6.

*Proof.* To prove this theorem, we begin by taking the expected form of equation (8):

$$E[\tilde{P}_2] = \frac{1}{m} (E[\tilde{\mu}_2 - \tilde{\omega}_2] - N_I y^* + N_P y^*).$$

We get the equation:

$$mE[\tilde{P}_2] + N_I x^* - N_P Y^* = E[\tilde{\mu}_2 - \tilde{\omega}_2]. \quad (52)$$

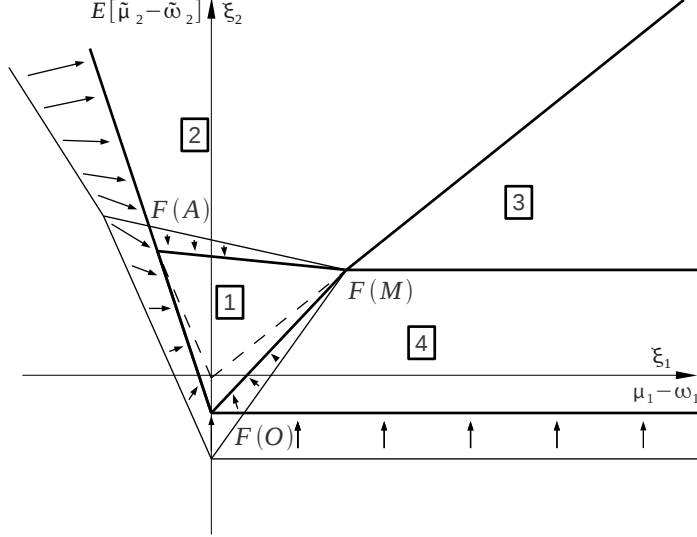


Figure 6: Changes on regions when the futures market is closed.

Hence  $\text{Var}[\tilde{P}_2] = V_2$ , a constant. Consider the mapping  $F_{NF} : \mathbb{R}_+^2 \rightarrow \mathbb{R}^2$  defined by:

$$F_{NF}(P_1, E[\tilde{P}_2]) = \begin{pmatrix} mP_1 - \frac{n_I C}{C + \alpha_I V_2} \max\{E[\tilde{P}_2] - P_1, 0\} \\ mE[\tilde{P}_2] + \frac{n_I C}{C + \alpha_I V_2} \max\{E[\tilde{P}_2] - P_1, 0\} - \frac{n_P P}{P\beta + \alpha_P V_2} \max\{P - E[\tilde{P}_2], 0\} \end{pmatrix}.$$

Formally, the analysis is identical to the one done in the basic case. We see now the validity of Table 2. The images  $F_{NF}(O)$ ,  $F_{NF}(A)$ , and  $F_{NF}(M)$  are easily computed:

$$\begin{aligned} F_{NF}(O) &= (0, -n_P P), \\ F_{NF}(A) &= P(-n_I, m + n_I), \\ F_{NF}(M) &= mP(1, 1). \end{aligned}$$

From this, one can find the images of all four regions. In other words, the image of  $O$  moves towards the origin. The image of  $M$  doesn't move. The image of  $A$  goes to the south-east (this is directly visible in the expressions above), in a way that is characterized in detail to prove the theorem. The properties concerning  $O$  and  $M$  are obvious. Concerning the image of  $A$ , we need to check two facts: (1)  $OF_{NF}(A)$  is steeper (in absolute value) than  $OF(A)$ ; (2)  $MF_{NF}(A)$  is flatter (in absolute value) than  $MF(A)$ . (1) We compare  $\rho + m/n_I$  with  $1 + m/n_I$ . The former can be rearranged as

$$\begin{aligned} 1 + m \frac{V_2}{\frac{N_P}{\alpha_P} + \frac{N_I}{\alpha_I} + \frac{N_S}{\alpha_S}} + \frac{m}{n_I} &= 1 + m \frac{C + \frac{V_2}{\frac{1}{\alpha_I} + \frac{1}{N_I} \left( \frac{N_P}{\alpha_P} + \frac{N_S}{\alpha_S} \right)}}{n_I C} \\ &= 1 + m \frac{C + \frac{\alpha_I V_2}{1 + \frac{\alpha_I}{N_I} \left( \frac{N_P}{\alpha_P} + \frac{N_S}{\alpha_S} \right)}}{n_I C} = 1 + \frac{m}{n_I} \frac{C + \frac{\alpha_I V_2}{1 + \frac{\alpha_I}{N_I} \left( \frac{N_P}{\alpha_P} + \frac{N_S}{\alpha_S} \right)}}{C + \alpha_I V_2} \end{aligned}$$

which is clearly smaller than the latter. (2) We have to compare the two vectors:

$$\begin{aligned} F(M) - F(A) &= P(m + n_I, -\rho n_I), \\ F_{NF}(M) - F_{NF}(A) &= P(m + n_I, -n_I) \end{aligned}$$

Clearly, the ratios of coordinates are such that the latter is flatter than the former because  $\rho > 1$  and  $\alpha_I V_2 > 0$ .  $\square$

**Prices and volatility.** The absence of a futures market impacts quantities as well as price levels and volatilities. For instance equations (7) and (8) suggest that lower values of  $\underline{X}^*$  and  $\underline{Y}^*$  lead to lower levels of the spot price at time 1, and also, possibly, at time 2.

Prices and quantities in the NF scenario are the following (they can be retrieved directly, or using Table 2 on the expressions in Appendix A):

$$P_1 = \frac{(m + (\underline{n}_I + \underline{n}_P))\frac{\xi_1}{m} + \underline{n}_I\frac{\xi_2}{m} + \underline{n}_I\underline{n}_Pm^{-1}P}{m + (\underline{n}_I + \underline{n}_P) + \underline{n}_I + \underline{n}_I\underline{n}_Pm^{-1}}, \quad (53)$$

$$E[\tilde{P}_2] = \frac{\underline{n}_I\frac{\xi_1}{m} + (m + \underline{n}_I)\frac{\xi_2}{m} + (m + \underline{n}_I)\underline{n}_Pm^{-1}P}{\underline{n}_I + (m + \underline{n}_I) + (m + \underline{n}_I)\underline{n}_Pm^{-1}}, \quad (54)$$

$$\tilde{P}_2 = \frac{\tilde{\xi}_2}{m} + \frac{\underline{n}_I\frac{\xi_1}{m} - ((m + \underline{n}_I)\underline{n}_Pm^{-1} + \underline{n}_I)\frac{\xi_2}{m} + (m + \underline{n}_I)\underline{n}_Pm^{-1}P}{\underline{n}_I + (m + \underline{n}_I) + (m + \underline{n}_I)\underline{n}_Pm^{-1}}, \quad (55)$$

$$X^* = \frac{-(m + \underline{n}_P)\frac{\xi_1}{m} + m\frac{\xi_2}{m} + \underline{n}_P P}{\underline{n}_I + (m + \underline{n}_I) + (m + \underline{n}_I)\underline{n}_Pm^{-1}}, \quad (56)$$

$$Y^* = \frac{-\underline{n}_I\frac{\xi_1}{m} - (m + \underline{n}_I)\frac{\xi_2}{m} + (m + 2\underline{n}_I)P}{\underline{n}_I + (m + \underline{n}_I) + (m + \underline{n}_I)\underline{n}_Pm^{-1}}. \quad (57)$$

Remark that  $\xi_1$  should be seen as random, notwithstanding the fact that we supposed in this model that markets are open only after its value has been revealed. In this view, the empirical variability of the prices depend directly on the variability of  $\xi_1$ . Let's assume first that  $\xi_1$  and  $\tilde{\xi}_2$  are independent. Later on, we can reason intuitively on positive or negative correlations.

We thus compare in the two scenarios the variability of  $P_1$  attributable to  $\xi_1$ :

$$\text{Var} \left[ \frac{\underline{n}_I\frac{\xi_1}{m}}{\underline{n}_I(\rho + 1) + m + \underline{n}_P\rho + \underline{n}_I\underline{n}_P\rho m^{-1}} \right]$$

with

$$\text{Var} \left[ \frac{\underline{n}_I\frac{\xi_1}{m}}{2\underline{n}_I + m + \underline{n}_P + \underline{n}_I\underline{n}_Pm^{-1}} \right].$$

As we have  $\rho > 1$  and  $\underline{n}_P > \underline{n}_I$ , the volatility of  $P_1$  is reduced by the presence of the futures market, at least if  $\underline{n}_I$  and  $\underline{n}_P$  are not too different. In fact, the reduction of the volatility by futures markets is not guaranteed. Assume for example that  $\alpha_I$  is large (or any other reason making global risk aversion substantial). Then,  $\underline{n}_I$  is very small, clearly making the volatility in the NF scenario smaller.

This case illustrates that financial market may “destabilize” markets, though the term is inappropriate since it only refers to a statistical property. Of course a higher price volatility doesn't mean a lower welfare, quite the contrary: more volatility means that prices are more effective/informative signals. The impact of markets on prices volatilities is often a naïve aspect of welfare analysis. We shall go further in section 6.

To understand the higher volatility, remark that the storer could react quite differently to different  $\xi_1$  under different market organizations. If the absence of futures frightens

the storers, so that they hardly store, their impact on the market in the second period would be negligible. On the contrary, if speculators were not very risk averse, they would accentuate the dependency of actual inventories on the current  $\xi_1$ . These more reactive actions will transport, in a sense, the volatility of the first period to the second one. This explanation is close to the analysis in [Newbery \(1987\)](#).