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A multi-factor model with time-varying and seasonal risk premiums for the natural gas market

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ABSTRACT

In this paper, we develop a quantitative model of the US natural gas market that explores its multi-factor structure and its time-varying and seasonal risk premiums. With weekly spot and futures prices we show that three factors are preferred to describe the futures term structure, and the time-varying risk premiums are also significant. Moreover, we found that the market implies a seasonal risk premium with two peaks and troughs in one year, which is important to correctly price the futures by maturity month. Finally, we link this seasonal risk premium to the uncertainty of the US natural gas demand and find a positive relationship between them. These results reveal the complex aspect of the market, and may have useful applications for other commodity sectors.

1. Introduction

Global natural gas markets have undergone significant changes in regulation in recent decades. The US natural gas market is now the largest one in the world and its deregulation started with The Natural Gas Policy Act in 1978. Since then, the market has become more competitive and relevant trading activities have greatly increased. Therefore it is important for both academia and industry to obtain a deep understanding of price movements and risk factors in the market.

The spot-based commodity models trace back to Brennan and Schwartz (1985). This early model does not consider the mean-reversion phenomenon and the Samuelson effect (i.e., the observation that the volatility of a commodity futures contract tends to increase when approaching its maturity) which are two properties usually seen in commodity markets, including natural gas. To incorporate these properties, Schwartz (1997) proposed a one-factor model where the spot log-price follows an Ornstein–Uhlenbeck process. However, the futures term structures derived under this model are too strict and inconsistent with empirical observations. In fact, the futures prices over the whole term curve are perfectly correlated. Moreover, the futures price volatility shrinks to zero in the long term, which is not the case in reality.

To solve these drawbacks, several two-factor models have been constructed in the literature. Broadly speaking these models can be divided into two types. The first type is based on Gibson and Schwartz (1990) where one factor is the spot price and the other is the stochastic convenience yield. The second type was introduced in Schwartz and Smith (2000) where one factor models short-term price deviations and the other models the long-term equilibrium price evolution (hereafter ST/LT). Schwartz and Smith also showed that both types are equivalent in nature. Under these models the futures prices are no longer perfectly correlated and so richer term structures can be produced. In addition, because of the long-term factor, the futures price volatility converges to a non-zero value in the long term, which is closer to actual situations. Between the two types, the Schwartz and Smith (2000) structure has advantages of being easy to interpret and having usually weakly correlated factors. Since then, a number of papers have extended the original ST/LT model to three factors by adding another short-term factor (hereafter 2ST/LT) and found evidence in favour of such an extension. Cortazar and Naranjo (2006) developed a general N-factor framework and found that the 2ST/LT model fits the crude oil futures term structure much better than the ST/LT model. Bhar and Lee (2011) also conducted a model comparison using crude oil futures. They found that the 2ST/LT model shows significant improvement and the ST/LT

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model is misspecified. Therefore, in this paper we take the Schwartz and Smith (2000) structure as the starting point for further development, and make a comparison between the ST/LT version and the 2ST/LT version.

As a special kind of commodity, natural gas exhibits significant seasonal behaviours which are well documented in much literature such as Manoliu and Tompaidis (2002) and Mirantes et al. (2012). Take crude oil as a counter example. One reason for the difference in their seasonality is their different demand patterns. In the US, natural gas is continuingly used as a fuel for heating purposes, and recently there has been a growing trend to use natural gas for marginal power generation in order to satisfy cooling needs. Therefore, the demand for natural gas has a seasonal pattern with two peaks in winter and summer respectively, and the weather conditions, especially the temperature, play key roles. Mu (2007) analysed such seasonal demand patterns and found significant weather impacts. On the contrary, crude oil is mainly used in the transportation and production industries which are not strongly affected by seasons. Another reason is due to their different physical structures. Compared with crude oil, natural gas is more costly to transport and store, which makes its market more difficult to smooth out its seasonal demand. The most common way to incorporate seasonality into a commodity model is to add a deterministic seasonal component in the spot price process. In this paper we use a sum of continuous trigonometric functions similar to Sørensen (2002).

For spot-based models, the spot price dynamics are directly specified under the real-world measure (hereafter $\mathbb{P}$). The martingale approach is then employed to price futures as expectations of the future spot price under an equivalent martingale measure (hereafter $\mathbb{Q}$) where the spot price process follows another dynamics. For diffusion cases, such changes in dynamics are captured by adjusting the drift terms, and risk premiums are then the differences in the drift terms. In this paper we define them as the drift terms under $\mathbb{Q}$ minus the drift terms under $\mathbb{P}$. The intuition behind the risk premiums becomes clear within the discussion of contango and normal backwardation, in which one considers the difference between $\mathbb{E}_{\mathbb{P}}[S_T]$ and the futures price, $F(0,T)=\mathbb{E}_{\mathbb{Q}}[S_T]$. If $\mathbb{E}_{\mathbb{P}}[S_T]>F(0,T)$ (normal backwardation), then the short futures hedger has weak bargaining power, which pushes the futures price down relative to the expected spot price. On the other hand, if $\mathbb{E}_{\mathbb{P}}[S_T]<F(0,T)$ (contango), then the long futures hedger has weak bargaining power, which pushes the futures price up. Clearly, in order to compare the two expectations, we only need to compare the drift terms under each measure. The classical setup is to assume constant risk premiums. However, there are also some papers supporting time-varying risk premiums in commodity markets. For example, Considine and Larson (2001) and Chiou Wei and Zhu (2006) found time-varying risk premiums in natural gas markets. To account for time-varying risk premiums in our models, we apply the framework in Duffee (2002) and Cheridito et al. (2007) and set the risk premiums as affine functions of state factors. Casassus and Collin-Dufresne (2005) adopted this approach under a stochastic convenience yield model and found time-varying risk premiums in silver, gold and copper markets. Cartea and Williams (2008) investigated the UK natural gas market under the ST/LT model with a time-varying risk premium whose estimation is not very sharp due to the limited amount of data they used. In this paper, we use a dataset covering wider ranges in both time-series and cross-section dimensions in order to obtain statistically significant results.

In terms of financial interpretations, the risk premium can be treated as the insurance paid by asset purchasers to hedge risk by entering into long positions in futures contracts. On the other side, the negative risk premium is the insurance paid by asset holders to hedge risk by entering into short positions in futures contracts. If there is a higher requirement for asset demand in some period, then the asset purchasers are more willing to hedge risk than the assets holders. This means the aggregate risk premium in this period is higher, and the prices of futures maturing in this period are pushed up by the asset purchasers. As mentioned earlier, the demand for natural gas in the US has a seasonal pattern with one peak in winter and another in summer. Thus it is possible that the risk premium in the US natural gas market also has some seasonality that is related to such a demand pattern. In the literature, seasonality in the risk premium has been considered by several authors. Villaplana (2003) modelled a seasonal jump risk premium in electricity markets. Cartea and Villaplana (2008) proposed a supply–demand model for electricity markets and obtained a seasonal risk premium that is related to demand volatility. Borovkova and Geman (2006) directly modelled natural gas forward curves and introduced a seasonal risk premium as a function of the forwards maturity month only. Jin et al. (2012) studied agricultural commodities and set a seasonal risk premium as a sum of trigonometric functions in the mean-reversion level of the convenience yield process under $\mathbb{Q}$. In this paper, we take a similar approach and specify two peaks in one year in the mean-reversion level of a short-term factor process under $\mathbb{Q}$.

This paper has three contributions. First, we extend the model of Cartea and Williams (2008) to three factors and justify such an extension. Using a rich dataset we obtain two significant time-varying risk premiums. Second, we model a seasonal risk premium in the form of a seasonal mean-reversion level under $\mathbb{Q}$ and find statistical justifications for this component. This multi-factor spot-based model with such a seasonal risk premium is new for energy markets. The two peaks in one year in the seasonal risk premium are also newly detected for natural gas. Third, we find a positive relationship between the obtained seasonal risk premium and the uncertainty of the US natural gas demand, which is also new in the literature in terms of exploring quantitative relationships between the risk premium and fundamental factors in natural gas markets.

The remainder of the paper proceeds as follows. In Section 2 we propose our models and derive futures prices. In Section 3 we present the data and estimation methodology. In Section 4 we provide and discuss empirical results. Section 5 concludes the paper.

2. Model and futures price

The 2ST/LT model extends the classic Schwartz and Smith (2000) ST/LT model by adding another short-term factor. The spot price is decomposed as the sum of three factors: one long-term factor modelling the equilibrium price evolution related to technology advancement, market structure change, resource discovery, etc; and two short-term factors capturing price deviations caused by temporary supply–demand imbalance or other short-term reasons.

The proposed Model 1 is a 2ST/LT version, and has a deterministic seasonal component, time-varying risk premiums and a seasonal risk premium. As usual, we define a probability space $(\Omega, \mathcal{F}, \mathbb{P})$ where the filtration $\{\mathcal{F}_t\}_{t\geqslant 0}$ is generated by Brownian motions $W_t=[W_{1,t}\ \ W_{2,t}\ \ W_{3,t}]$. The spot price process under $\mathbb{P}$ is then modelled as

$$\log S_t = f(t) + X_{1,t} + X_{2,t} + Y_t \tag{1a}$$

$$dX_{1,t} = -\kappa_1 X_{1,t}dt + \sigma_1 dW_{1,t} \tag{1b}$$

$$dX_{2,t} = -\kappa_2 X_{2,t}dt + \sigma_2 dW_{2,t} \tag{1c}$$

$$dY_t = \mu dt + \sigma_3 dW_{3,t}. \tag{1d}$$

In the above equations, $f(t)$ is the deterministic seasonal component, $X_{1,t}$ and $X_{2,t}$ are the two short-term factors, and Y_t is the long-term factor. $W_{1,t}$, $W_{2,t}$ and $W_{3,t}$ are correlated Brownian motions such that $dW_{i,t}dW_{j,t}=\rho_{ij}dt$. κ_1 and κ_2 represent the mean-reversion speeds of short-term price deviations in $X_{1,t}$ and $X_{2,t}$ respectively, while μ stands for the average growth rate of the long-term equilibrium price evolution. σ_1, σ_2 and σ_3 are the volatility parameters.

There are several ways to specify the deterministic seasonal component $f(t)$ in the commodities literature. Some papers such as Lucia and Schwartz (2002) use dummy variables. In this paper, we follow the