

MODELING, VALUATION AND RISK MANAGEMENT OF ASSETS AND DERIVATIVES IN ENERGY AND SHIPPING

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Abstract

The energy and shipping markets operate in an environment exposed to a variety of risks responsible for the high volatility of the prices of oil, natural gas, electricity and freight rates. The need to control this price volatility has prompted the development of valuation and risk management methods for energy assets and their derivatives analogous to those widely used in the fixed income, equity and foreign exchange markets. This paper reviews recent developments in this field emphasizing quantitative methods and their application in energy and shipping.

Stochastic models for the spot price of oil, natural gas and electricity and of their futures curves are reviewed. The pricing of vanilla and exotic derivatives for jump-diffusions is discussed using recent valuation methods based on complex characteristic functions and Fourier integration. Recent analytical results in stochastic optimal control theory are reviewed and their use is proposed for the solution of a number of complex risk management problems involving portfolios of energy assets and their derivatives.

Applications discussed include the valuation of storage facilities for natural gas, oil and other fuels, the optimal operation of flexible hydrocarbon reservoirs, the hedging of fuel costs in the transportation and energy sectors, the valuation of seaborne energy cargoes – oil, products, LNG – transported in tankers, the fuel efficient navigation and weather routing of shipping fleets, the valuation and hedging of power plants and refineries, the pricing of credit risk and derivative securities in shipping and the valuation of electricity storage facilities for offshore wind farms.

1. ENERGY COMMODITY PRICE MODELS

Background

The past several decades have witnessed the emergence and rapid development of the fields of financial engineering and derivatives. Grown out of Paul Samuelson's foundational insights on the relationship between informationally efficient markets and the random walk and his introduction of the lognormal diffusion model of security prices, a wide range of stochastic models of asset prices and arbitrage free valuation methods were developed for the pricing of derivatives written on financial securities, real assets and other variables. The use of these models and pricing methods in the fixed income, equity, foreign exchange and credit markets is growing as is the complexity of the mathematical, econometric and filtering methods necessary for their implementation. More recently, these methods have been adapted to the energy and shipping sectors in order to control the high volatility of energy prices and freight rates and spur new investment.

Spot Price Models

Energy commodity prices are characterized by idiosyncrasies not encountered in the financial markets. The volatility of the price of oil, natural gas and especially electricity is a lot larger than that of currencies, interest rates and equities. Energy prices often exhibit mean reversion, seasonality, sharp and asymmetric spikes that require the development of advanced price models and derivative valuation methods, extensions of the Black-Scholes-Merton stock option pricing formula. Moreover, a complex interaction often exists between attributes of the spot physical commodity and its forward contracts and other derivatives, not present for financial securities and their derivatives which settle electronically and do not require the delivery of a physical asset. This requires the use of the extended risk-neutral valuation method of derivatives written on real assets and other variables that are not tradable [Ross (1976)].

Standard reduced form stochastic models for the spot price of oil and natural gas are diffusions which account for mean reversion, seasonality and depend on hidden economic factors. They include a stochastic convenience yield – the implied dividend received by the owner of the commodity held in storage – and a long-term stochastic equilibrium price to which the spot price mean reverts. The two-factor spot price models of Gibson and Schwartz (1990), Schwartz (1997) and Smith and Schwartz (2000) model the spot price and its factors as diffusions and permit the explicit valuation of futures and forward contracts and options written on the spot and its forwards [Hull (2003)]. More general spot price models that may include stochastic volatility and jumps are discussed in Clewlow and Strickland (2000) and London (2007). In the study by Cortazar and Naranjo (2006) the entire oil futures curve and its volatility term structure are shown to be very well modeled by a four-factor spot price Gaussian model which was estimated by Kalman filtering.

Stochastic models for the evolution of the electricity prices must account for sharp and asymmetric spikes, strong mean reversion, jumps and a dependence on structural factors affecting the electricity market. Reduced form stochastic models of electricity prices are usually jump-diffusions and Levy processes. An example is the jump-diffusion model of Kou (2002) which permits the independent parametric adjustment of the tail thicknesses of its probability distribution and allows the explicit pricing of electricity derivatives. Other models are discussed in Eydeland and Wolyniec (2003) and London (2007).

Forward Curve Models

Crude oil and natural gas have liquid futures contracts trading on the New York Mercantile Exchange (Nymex) and other exchanges with tenors of several years. For these commodities arbitrage-free forward curve models have been developed by Miltersen and Schwartz (1998). They accept as input the market prices of liquid futures and lead to the pricing of a number of other derivatives. Arbitrage-free models for the spot price follow from futures contracts of small tenors.

The modeling of the oil and natural gas futures curve is based on the Heath-Jarrow-Morton (HJM) framework developed for the arbitrage-free modeling of the term structure of interest rates. A principal task of the HJM framework is the parameterization of the volatility and correlation structure of the futures curve by a small number of independent factors using a Principal Components analysis. Calls, puts, swaps, caps and their options written on futures contracts may then be valued explicitly as in the interest rate markets for use in energy risk management applications. [Hull (2003), Musiela and Rutkowski (2005)].

Energy Derivatives

In addition to the standard derivatives discussed above, more complex derivatives have been introduced in the energy markets reflecting the economics of the energy sector. In particular, power plants are exposed to the spot/futures price difference of two energy commodities – natural gas/electricity, coal/electricity --, refineries are exposed to the price differentials of two fuels – crude oil/gasoline, crude oil/jet fuel -- and oil and natural gas pipelines and electricity transmission lines are exposed to the price differentials of the same spot commodity at two different geographical locations.

A partial list of exotic derivatives used for the valuation, hedging and risk management of energy assets include options on the spread between two futures contracts with different expirations written on the same commodity, options on the price difference of two futures contracts with the same expiration written on two separate commodities, options to exchange two spot commodities or their futures, average-price and average-strike Asian options, Barrier options which are exercised when the commodity price crosses a threshold and American swing options for the delivery of an uncertain amount of the commodity. A discussion of these and other exotic energy derivatives is presented in

Clelow and Strickland (2000), Eydeland and Wolyniec (2003), Geman (2005) and London (2007).

Exotic energy derivatives are complex to price and hedge for advanced commodity price models. Furthermore, spread derivatives depend not only on the volatility but also on the correlation between various spot/futures contracts which may be challenging to model and calibrate to market prices. Consequently, the development of accurate stochastic price models and pricing methods for exotic derivatives and spread options may be particularly helpful for the valuation, hedging and risk management of energy assets.

2. VALUATION AND HEDGING OF DERIVATIVES

Vanilla Derivatives for Jump-Diffusions

The pricing of derivatives written on a financial security, a spot commodity, or another variable – the underlying -- may be carried out by using the fundamental principles of risk-neutral valuation described in Hull (2003). When the underlying is a non-tradable – temperature – an associated market price of risk process enters in the derivative price which must be estimated from the prices of traded instruments. Otherwise, the fundamental economic insight of risk-neutral pricing and the associated mathematical techniques apply over a wide range of assets and stochastic models used for the modeling of the underlying process.

A standard derivative pricing method for the wide class of jump-diffusion processes is based on the derivation of a risk-neutral probability measure under which European derivative prices may be expressed as conditional expectations of a payoff at a specified horizon [Duffie (2001), Shreve (2004), Musiela and Rutkowski (2005)]. Derivative prices expressed as conditional expectations may be evaluated explicitly in the form of Fourier integrals of the complex characteristic function of the jump-diffusion by using the methods developed by Heston (1993), Carr and Madan (1998), Duffie, Pan and Singleton (2000) and Lewis (2005). The use of this derivative pricing method in practice for the modeling of the equity implied volatility surface and the calibration of a wide range of jump-diffusion models are discussed in Gatheral (2006).

Derivative prices expressed in the form of Fourier integrals allow the explicit evaluation of the derivative sensitivities known as the Greeks, they permit the analytical derivation of the stochastic process followed by the derivative price itself by using the Ito-Doeblin formula and often allow the explicit pricing of European derivatives with more general payoffs. The evaluation of Fourier integrals may be carried out efficiently by complex contour integration, numerical integration or Fast Fourier Transform techniques.

The valuation of American options for jump-diffusions and the optimal stopping problems that arise when early exercise is permitted is discussed in Oksendal and Sulem (2005). When the use of analytical techniques is not possible for the approximation of American options and the evaluation of the early exercise boundary, the Monte Carlo

simulation methods described in Glasserman (2004) may be used.

Exotic Derivatives for Jump-Diffusions

The valuation of a number of exotic derivatives is considerably more complex than their vanilla counterparts because their price depends on the path of the underlying process. Typical examples are Barrier and Asian options. Therefore, the price of exotic derivatives is more sensitive on the structure of the underlying stochastic process than is the price of vanilla calls and puts. Consequently, the choice of the underlying process and the subsequent pricing and hedging of exotic derivatives may be a task of considerable complexity, a topic discussed for equities by Gatheral (2006).

For the geometric Brownian motion with constant drift and volatility explicit prices of a number of exotic derivatives are derived in Shreve (2004). When the underlying process follows a jump-diffusion, the pricing of exotic derivatives by Fourier methods leads to Wiener-Hopf problems in the complex plane the factorization of which is often possible analytically. This is the case for the jump-diffusion model of Kou (2002) which leads to the explicit valuation of Barrier options. These analytical results are developed in Cont and Tankov (2004) where the class of Levy stochastic processes is also studied.

The extension of these Fourier methods to the valuation of options on spread contracts and other complex energy derivatives is discussed in London (2007). In the same reference the derivation of the characteristic functions of a number of jump diffusion models of energy prices is presented along with the valuation of weather derivatives.

Statistical Inference of Asset Price Models

Asset price models usually contain a number of parameters that need to be estimated upon calibration of the model against market prices. This may be carried out by using the econometric techniques presented in Cambell, Lo and MacKinley (1997), Lo and MacKinley (2001), Greene (2000) and Singleton (2006).

Stochastic models of energy commodity prices contain hidden factors – stochastic drifts, the convenience yield, volatilities, correlations -- often modeled as diffusions. Shipping indices and cargo vessel prices also depend on observable and hidden factors. The estimation of such models may be carried out by discretizing the time series and casting them in state space form by using the methods described in Durbin and Koopman (2001). The simultaneous inference of model parameters, hidden factors and the loadings of observable factors may then be carried out by estimating linear or nonlinear state space models using the linear, extended and dual Kalman filters and in non-Gaussian settings the particle filters discussed in Haykin (2001).

These advanced statistical inference techniques are finding increasing use in the securities markets for the modeling of asset prices and for use in a wide range of trading

strategies. In the energy and shipping sectors these techniques may be used to model commodity futures curves, estimate linear dynamic factor models with time dependent stochastic loadings or nonlinear structural form models of power prices and shipping freight rates which often depend on nonlinearities in the supply and demand schedules of the underlying markets.

Stochastic Optimal Control Methods

The availability of analytical models governing the evolution of spot commodity prices and their derivatives, allow the formulation and solution of a wide range of valuation and hedging problems involving energy assets and their derivatives. The resulting stochastic dynamic programming problems are often possible to treat analytically by using the stochastic optimal control methods presented in Yong and Zhou (1999) for diffusions with time dependent coefficients. These results follow from the solution of the Hamilton-Jacobi-Belman (HJB) partial differential equation or the Pontryagin Stochastic Maximum Principle and its connection to backwards stochastic differential equations. Extensions of these stochastic optimal control methods for underlying processes that follow diffusions with stochastic coefficients are discussed in Lewis (2005). Stochastic control methods for jump-diffusions and the treatment of the associated integro-differential equations are discussed in Oksendal and Sulem (2005).

3. APPLICATIONS

The stochastic price models, derivative valuation methods and stochastic optimal control algorithms presented above have found widespread use in the securities markets. A number of applications drawn from the energy and shipping sectors are discussed below.

Valuation of Natural Gas and Oil Storage

Storage facilities for natural gas are assets that enable the transfer of power generation capacity between two time periods in response to supply and demand fluctuations. Such fluctuations are affected by the different seasonal variations of the natural gas and electricity prices, the former usually being higher and more volatile during the winter and the latter often being a lot higher during the summer.

The availability of inexpensive gas storage facilities, and the need to invest in new capacity, allows the low cost shifting of cheap summer production and storage of gas into the winter season. Moreover, the availability of gas storage facilities allow the quick delivery of natural gas when demand peaks, circumventing the need for expensive new production. These economic drivers call for the valuation and optimal operation of storage facilities for natural gas and other fuels, in the face of stochastic gas prices which are assumed to be unaffected by the availability of storage.

Analogous considerations apply to investments in crude oil storage facilities either onshore or in tanker fleets. Depending on the global supply and demand fundamentals and other economic factors, the crude oil futures curve may be trading in contango, backwardation or in a composite formation, leading to conditions that favor storing oil or selling it in the spot market, respectively. The dynamics of the entire oil futures curve and its volatility structure was shown by Cortazar and Naranjo (2006) to be very well modeled by a four-factor spot price model estimated by Kalman filtering.

Consequently, the storage valuation problem may be cast in a stochastic dynamic programming framework that relies on the underlying analytical models of the commodity spot prices, futures curve dynamics and their derivatives, as outlined above. In its generality, this valuation problem reduces to the determination of optimal storage in/out-flows given the dynamics of the commodity futures curve.

Valuation of Flexible Hydrocarbon Reservoirs

The optimal dynamic management of proven but undeveloped hydrocarbon reservoirs and flexible oil fields leads to a sequence of decisions analogous to those described above for above-ground storage facilities. When significant irreversible investments with option like value are necessary for the development of flexible hydrocarbon fields, the extended valuation framework of Real Options is needed. Its development is presented in Dixit and Pindyck (1994) and a number of applications are discussed in Brennan and Trigeorgis (2000) and Copeland and Antikarov (2001). Given a spot price or HJM model for the oil and natural gas futures curve and its derivatives, the operation of flexible hydrocarbon fields may be reduced to a stochastic dynamic programming problem leading to the determination of optimal investment and hydrocarbon extraction flows. A number of real projects where these valuation methods are applicable are presented in Ronn (2002).

Hedging of Fuel Costs

The risk management of fuel costs in the transportation and energy sectors entails the hedging of commitments to purchase or deliver energy commodities – crude oil, natural gas, aviation jet fuel, gasoline, heating oil and shipping bunker by various entities – refineries, utilities, airlines and shipping companies. An objective of such hedging programs is the minimization of the variance of the commodity price exposures over a given horizon. Variance minimizing quadratic hedges of complex derivative exposures using simpler securities is common in the financial markets and may be reduced to the solution of a stochastic dynamic programming problem [Yong and Zhou (1999) and Jouini, Cvitanic and Musiela (2001)].

A fuel cost hedging program may be implemented by using a combination of physical storage and the futures market. Such a hedging task faces a number of challenges, including commodity price and volume uncertainty, a decreasing liquidity of futures contracts of increasing tenor, an increasing volatility of futures contracts of decreasing

tenor that need to be rolled over and exposure to basis risk when liquid futures contracts for the fuel of interest do not exist. The solution of the resulting dynamic optimization problem may be carried out by taking advantage of the analytical modeling, pricing and optimal control techniques outlined above. The complexity of such hedging programs is considerable as is highlighted by the collapse of the stacked hedges of Mettalgeshellschaft studied in Culp and Miller (1999).

Valuation of Seaborne Energy Cargoes

Crude oil, Liquefied Natural Gas and other liquid energy cargoes transported in tanker fleets may be traded while the cargo is in transit. This is akin to the optimal financial management of energy commodities in movable storage. Here, the location and speed of the tankers enter as controls in a stochastic dynamic programming framework which may be treated with the analytical techniques described above. The timing, sales price and port of delivery of the energy cargo are variables that may be selected in a value maximizing manner while the commodity is in transit. These decisions must take into consideration the shape of the oil or natural gas futures curves which may be trading in contango, backwardation or in a composite formation. Moreover, since a large portion of the above-ground crude oil is in transit, the aggregate tonnage and average speed of crude oil tanker fleets may have a material impact upon the crude oil convenience yield, the shape of its futures term structure and its impact on the valuation of seaborne oil.

A similar set of decisions faces firms transporting Liquefied Natural Gas. The LNG market is not as liquid or global as the oil market, yet it is likely to mature in the future in light of the growing demand for natural gas for the generation electricity.

Fuel Efficient Navigation and Weather Routing of Shipping Fleets

The shipping industry consumes approximately 5% of the world oil production in the form of bunker fuels. Assuming a daily world oil production of 87 million barrels and a long term price of oil of \$80 per barrel, the daily bunker fuel costs for the shipping industry are estimated at \$320 million dollars. The long term daily average freight rate revenue is harder to estimate and is assumed over twice the daily bunker fuel costs.

The selection of the optimal speed and route of cargo vessels exposed to weather, stochastic freight rates and subject to the constraints imposed by the charter contract, cargo loading schedules, port and other fees, leads to a complex stochastic dynamic programming problem. The ship resistance, propulsion and seakeeping characteristics may be supplied by the shipowner, estimated from models or inferred from real-time measurements of the ship speed, propeller revolutions, engine performance, response records in a seastate using extended Kalman filtering methods. Using a reduced form or structural stochastic price model for the shipping freight rates, optimal weather routing and scheduling strategies may be derived analytically aiming to minimize the fuel consumption, reduce the likelihood of damage in severe weather and maximize freight

rate revenue over single or consecutive voyages. A cumulative 10% reduction in bunker fuel costs, increase in freight rate revenue and eventually revenue from the trading of carbon emission credits, would translate into a \$60 million increase in the daily net income of the shipping industry. The promise of these advanced dynamic optimization algorithms is underscored by their adoption by the aviation industry for the optimal routing of commercial jets [“Calculating Costs in the Clouds”, The Wall Street Journal, March 6, 2007].

Valuation and Hedging of Power Plants and Refineries

The optimal economic dispatch of power plants presents a challenging problem that depends in part on the price differential of two energy commodities. The input commodity is usually a fuel – natural gas or oil – which may be traded in the spot and forward markets. The output commodity is electricity which cannot be stored, it trades into a spot cash market and may not have liquid forward contracts, as discussed by Joskow (2006).

In simple cases, the valuation of power generating units may be reduced to the pricing of a strip of options written on the price differentials of electricity and the input fuel, for example natural gas. Given analytical price models for the price of the input fuel and electricity, the power plant valuation and hedging problem may be based on the pricing of these spark-spread options which may be available explicitly. In more general settings where operational constraints apply, the valuation problem may be cast in a stochastic dynamic programming framework which may benefit from the use of the analytical modeling and hedging methods outlined above. A similar set of issues arise in the valuation and hedging of refineries which process crude oil, which has a well developed spot and futures market, into products – gasoline, heating oil, jet fuel -- which often do not have actively traded forward contracts. The use of this general valuation and hedging methodology in practice is presented in Eydeland and Wolyniec (2003).

Valuation of Shipping Securities and Their Derivatives

Shipping firms finance their fleets by issuing securities -- publicly traded or privately placed debt and equity [Stopford (1997), Grammenos (2002)]. Shipping is an industry where its underlying commodity-like assets – the cargo vessels – may be traded in the second-hand market where they have observable – albeit illiquid -- prices. The value of a shipping firm – the sum of its debt and equity securities -- may however differ from the price of its vessels because of chartering and other value enhancing financial strategies implemented by shipowners. As in other energy commodity markets, identifying the factors that impact the shipping freight rates and vessel prices is an essential first step towards the development of firm value models for the pricing of debt and equity securities and their derivatives,.

The credit risk of shipping firms may be valued by using a hybrid firm value method

which blends the structural method of Merton (1974) with the reduced form intensity method of Duffie and Singleton (2003) and Lando (2004). Intensity models appear particularly attractive for the pricing of credit risk in the volatile shipping sector. Factors that affect the yield premia of shipping bonds may be identified and used to estimate affine models of the hazard rate in intensity models. This allows the use of the entire pricing and statistical inference machinery developed for the modeling of the default-free term structure of interest rates. Explicit expressions follow for the likelihood of default, prices of high-yield bonds under various recovery assumptions and the pricing of a wide range of derivatives written on the assets of a shipping firm and its debt and equity securities accounting for counterparty risk [Ammann (2001)].

The market for shipping derivatives includes Forward Freight Agreements (FFAs), their derivatives [Koekebakker, Adland and Sodal (2007)] and the young market of Forward Ship Value Agreements [Adland, Jia and Koekebakker (2004)]. These and other derivatives written on shipping securities -- debt and equity -- may be structured and valued using the vanilla and exotic energy derivative valuation methods discussed above.

The above valuation framework draws upon recent developments on the pricing of credit risk and is also applicable to energy firms who own physical commodity-like assets that may be traded. In the case of the shipping sector, this integrated valuation framework may be used to guide a wide range of financial decisions taken by shipowners. They include the financing of a new-building program, fleet expansion or contraction via the second-hand market, degree of leverage, dividend policy, asset sales, the issuance of vanilla or structured securities and the use of derivatives for risk management.

Valuation of Electricity Storage Facilities for Offshore Wind Farms

Wind as an input fuel is an ample renewable natural resource, yet its availability is unpredictable. Consequently the electricity generated from a wind farm is also unpredictable and hence may be sold in the spot market at low prices when electricity demand is low, for example overnight. Therefore, investments in large scale storage facilities for electricity generated by wind farms may be economically attractive since they would permit the sale of electricity when prices peak.

Such storage facilities may be water tanks above/below sea level of optimal capacity and height/draft where water is pumped in/out when electricity prices are low. When electricity prices peak the water would be released from/in the tanks through water turbines similar to those used in hydroelectric power plants. The roundtrip efficiency of this cycle is estimated to be 60-70%. In the case of offshore wind farms ample seawater is available for use in such “electricity storage” facilities.

The valuation and optimal economic operation of such “electricity storage” depends on the short term volatility and longer term fluctuations of electricity prices. Therefore its value is analogous to that derived from natural gas storage. The availability of a stochastic price model for electricity allows the valuation of such storage facilities as

outlined above. The results of this analysis would suggest the optimal turnover frequency of the water held in storage, the optimal number, size and height of the storage tanks and the value derived from such an investment that would justify its cost.

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