CHAPTER 23

# Weather, Energy, and Insurance Derivatives

The most common underlying variables in derivatives contracts are stock prices, exchange rates, interest rates, and commodity prices. The futures, forward, option, and swap contracts on these variables have been outstandingly successful. As we discussed in Chapter 21, credit derivatives have also become very popular in recent years. Chapter 22 shows that one way dealers have expanded the derivatives market is by developing nonstandard (or exotic) structures for defining payoffs. This chapter discusses another way they have expanded the market. This is by trading derivatives on what might be termed "non-mainstream" underlying variables.

The chapter examines the products that have been developed to manage weather risk, energy price risk, and insurance risks. The markets that we will talk about are in some cases in the early stages of their development. As they evolve we may well see significant changes in both the products that are offered and the ways they are used.

## 23.1 REVIEW OF PRICING ISSUES

In Chapters 11 and 13, we explained the risk-neutral valuation result. This involves pricing the derivative on the assumption that investors are risk neutral. The expected payoff is calculated in a risk-neutral world and then discounted at the risk-free interest rate. The approach gives the correct price—not just in a risk-neutral world, but in all other worlds as well.

An alternative pricing approach sometimes adopted is to use historical data to calculate the expected payoff and then discount this expected payoff at the risk free rate to obtain the price. We will refer to this as the historical data approach. Historical data give an estimate of the expected payoff in the real world. It follows that the historical data approach is correct only when the expected payoff from the derivative is the same in both the real world and the risk-neutral world.

We showed in Section 11.7 that when we move from the real world to the risk-neutral world, the volatilities of variables remain the same, but their expected growth rates are liable to change. For example, the expected growth rate of a stock market index decreases by perhaps 4% or 5% when we move from the real world to the risk-neutral world. The expected growth rate of a variable can reasonably be assumed to be the same in both the real world and the risk-neutral world if the variable has zero systematic risk so that percentage changes in the variable have zero correlation with stock market returns.[1] We can deduce from this that the historical data approach to valuing a derivative gives the right answer if all underlying variables have zero systematic risk. A common feature of most of the derivatives we will consider in this chapter is that the historical data approach can be used. The underlying variables can reasonably be assumed to have zero systematic risk.

## 23.2 WEATHER DERIVATIVES

Many companies are in the position where their performance is liable to be adversely affected by the weather.[2] It makes sense for these companies to consider hedging their weather risk in much the same way as they hedge foreign exchange or interest rate risks.

The first over-the-counter weather derivatives were introduced in 1997. To understand how they work, we explain two variables:

HDD: Heating degree days

CDD: Cooling degree days

A day's HDD is defined as

$$\text{HDD} = \max(0,\ 65 - A)$$

and a day's CDD is defined as

$$\text{CDD} = \max(0,\ A - 65)$$

where $A$ is the average of the highest and lowest temperature during the day at a specified weather station, measured in degrees Fahrenheit. For example, if the maximum temperature during a day (midnight to midnight) is 68° Fahrenheit and the minimum temperature is 44° Fahrenheit, then $A = 56$. The daily HDD is then 9 and the daily CDD is 0.

A typical over-the-counter product is a forward or option contract providing a payoff dependent on the cumulative HDD or CDD during a month (i.e., the total of the HDDs or CDDs for every day in the month). For example, a dealer could in January 2004 sell a client a call option on the cumulative HDD during February 2005 at the Chicago O'Hare Airport weather station with a strike price of 700 and a payment rate of \$10,000 per degree day. If the actual cumulative HDD is 820, the payoff is \$1.2 million. Contracts often include a payment cap. If the payment cap in our example is \$1.5 million, the contract is the equivalent of a bull spread. The client has a long call option on cumulative HDD with a strike price of 700 and a short call option with a strike price of 850.

A day's HDD is a measure of the volume of energy required for heating during the day. A day's CDD is a measure of the volume of energy required for cooling during the day. Most weather derivative contracts are entered into by energy producers and energy consumers. But retailers, supermarket chains, food and drink manufacturers, health service companies, agricultural companies, and companies in the leisure industry are also potential users of weather derivatives. The Weather Risk Management Association

[1] We will discuss this further in Chapter 31.

[2] The US Department of Energy has estimated that one-seventh of the US economy is subject to weather risk.

(www.wrma.org) has been formed to serve the interests of the weather risk management industry.

In September 1999 the Chicago Mercantile Exchange began trading weather futures and European options on weather futures. The contracts are on the cumulative HDD and CDD for a month observed at a weather station.[3] The contracts are settled in cash just after the end of the month once the HDD and CDD are known. One futures contract is on $100 times the cumulative HDD or CDD. The HDD and CDD are calculated by a company, Earth Satellite Corporation, using automated data-collection equipment.

The temperature at a certain location can reasonably be assumed to have zero systematic risk. It follows from Section 23.1 that weather derivatives can be priced using the historical data approach. Consider, for example, the call option on the February 2005 HDD at Chicago O'Hare airport mentioned earlier. We could collect 50 years of data and estimate a probability distribution for the HDD in February. This in turn could be used to provide a probability distribution for the option payoff. Our estimate of the value of the option would be the mean of this distribution discounted at the risk-free rate. We might want to adjust the probability distribution for temperature trends. For example, a linear regression might show that (perhaps because of global warming) the HDD in February is decreasing at a rate of 10 per year on average. If so the output from the regression could be used to estimate a trend-adjusted probability distribution for the HDD in February 2005.

## 23.3 ENERGY DERIVATIVES

Energy companies are among the most active and sophisticated users of derivatives. Many energy products trade in both the over-the-counter market and on exchanges. In this section we will examine the trading in crude oil, natural gas, and electricity derivatives.

### Crude Oil

Crude oil is one of the most important commodities in the world, with global demand amounting to about 80 million barrels daily. Ten-year fixed-price supply contracts have been commonplace in the over-the-counter market for many years. These are swaps where oil at a fixed price is exchanged for oil at a floating price.

In the 1970s the price of oil was highly volatile. The 1973 war in the Middle East led to a tripling of oil prices. The fall of the Shah of Iran in the late 1970s again increased prices. These events led oil producers and users to a realization that they needed more sophisticated tools for managing oil-price risk. In the 1980s both the over-the-counter market and the exchange-traded market developed products to meet this need.

In the over-the-counter market, virtually any derivative that is available on common stocks or stock indices is now available with oil as the underlying asset. Swaps, forward contracts, and options are popular. Contracts sometimes require settlement in cash and sometimes require settlement by physical delivery (i.e., by delivery of the oil).

[3] The CME has introduced contracts for 10 different weather stations (Atlanta, Chicago, Cincinnati, Dallas, Des Moines, Las Vegas, New York, Philadelphia, Portland, and Tucson).

Exchange-traded contracts are also popular. The New York Mercantile Exchange (NYMEX) and the International Petroleum Exchange (IPE) trade a number of oil futures and futures options contracts. Some of the futures contracts are settled in cash; others are settled by physical delivery. For example the Brent crude oil futures traded on the IPE has cash settlement based on the Brent index price; the light sweet crude oil futures traded on NYMEX requires physical delivery. In both cases the amount of oil underlying one contract is 1,000 barrels. NYMEX also trades popular contracts on two refined products: heating oil and gasoline. In both cases one contract is for the delivery of 42,000 gallons.

## Natural Gas

The natural gas industry throughout the world has been going through a period of deregulation and the elimination of government monopolies. The supplier of natural gas is now not necessarily the same company as the producer of the gas. Suppliers are faced with the problem of meeting daily demand.

A typical over-the-counter contract is for the delivery of a specified amount of natural gas at a roughly uniform rate over a one-month period. Forward contracts, options, and swaps are available in the over-the-counter market. The seller of gas is usually responsible for moving the gas through pipelines to the specified location.

NYMEX trades a contract for the delivery of 10,000 million British thermal units of natural gas. The contract, if not closed out, requires physical delivery to be made during the delivery month at a roughly uniform rate to a particular hub in Louisiana. The IPE trades a similar contract in London.

## Electricity

Electricity is an unusual commodity because it cannot easily be stored.[4] The maximum supply of electricity in a region at any moment is determined by the maximum capacity of all the electricity-producing plants in the region. In the United States there are 140 regions known as *control areas*. Demand and supply are first matched within a control area, and any excess power is sold to other control areas. It is this excess power that constitutes the wholesale market for electricity. The ability of one control area to sell power to another control area depends on the transmission capacity of the lines between the two areas. Transmission from one area to another involves a transmission cost, charged by the owner of the line, and there are generally some transmission or energy losses.

A major use of electricity is for air-conditioning systems. As a result the demand for electricity, and therefore its price, is much greater in the summer months than in the winter months. The nonstorability of electricity causes occasional very large movements in the spot price. Heat waves have been known to increase the spot price by as much as 1000% for short periods of time.

Like natural gas, electricity has been going through a period of deregulation and the elimination of government monopolies. This has been accompanied by the development of an electricity derivatives market. NYMEX now trades a futures contract on the price

[4] Electricity producers with spare capacity sometimes use it to pump water to the top of their hydroelectric plants so that it can be used to produce electricity at a later time. This is the closest they can get to storing this commodity.

of electricity, and there is an active over-the-counter market in forward contracts, options, and swaps. A typical contract (exchange traded or over the counter) allows one side to receive a specified number of megawatt-hours for a specified price at a specified location during a particular month. In a 5 × 8 contract, power is received for 5 days a week (Monday to Friday) during the off-peak period (11 p.m. to 7 a.m.) for the specified month. In a 5 × 16 contract, power is received 5 days a week during the on-peak period (7 a.m. to 11 p.m.) for the specified month. In a 7 × 24 contract, it is received around the clock every day during the month. Option contracts have either daily exercise or monthly exercise. In the case of daily exercise, the option holder can choose on each day of the month (by giving one day's notice) to receive the specified amount of power at the specified strike price. When there is monthly exercise a single decision on whether to receive power for the whole month at the specified strike price is made at the beginning of the month.

An interesting contract in electricity and natural gas markets is what is known as a *swing option* or *take-and-pay option*. In this contract a minimum and maximum for the amount of power that must be purchased at a certain price by the option holder is specified for each day during a month and for the month in total. The option holder can change (or swing) the rate at which the power is purchased during the month, but usually there is a limit on the total number of changes that can be made.

## Modeling Energy Prices

A realistic model for a energy and other commodity prices should incorporate both mean reversion and volatility. One possible model is:

$$d \ln S = [\theta(t) - a \ln S]\, dt + \sigma\, dz \tag{23.1}$$

where $S$ is the energy price, and $a$ and $\sigma$ are constant parameters. The $\theta(t)$ term captures seasonality and trends. In Chapter 31 we will show how to construct a trinomial tree for the model in equation (23.1) with $\theta(t)$ being estimated from futures prices. The parameters $a$ and $\sigma$ can be estimated from historical data.

The parameters $a$ and $\sigma$ are different for different sources of energy. For crude oil, the reversion rate parameter $a$ in equation (23.1) is about 0.5 and the volatility parameter $\sigma$ is about 20%; for natural gas, $a$ is about 1.0 and $\sigma$ is about 40%; for electricity, $a$ is typically between 10 and 20, while $\sigma$ is 100 to 200%. The seasonality of electricity prices is also greater.[5]

## How an Energy Producer Can Hedge Risks

There are two components to the risks facing an energy producer. One is the price risk; the other is the volume risk. Although prices do adjust to reflect volumes, there is a less-than-perfect relationship between the two, and energy producers have to take both into account when developing a hedging strategy. The price risk can be hedged using the energy derivative contracts discussed in this section. The volume risks can be hedged using the weather derivatives discussed in the previous section.

[5] For a fuller discussion of the spot price behavior of energy products, see D. Pilipovic, *Energy Risk*. New York: McGraw-Hill, 1997.

Define:

$Y$: Profit for a month

$P$: Average energy prices for the month

$T$: Relevant temperature variable (HDD or CDD) for the month

An energy producer can use historical data to obtain a best-fit linear regression relationship of the form

$$Y = a + bP + cT + \epsilon$$

where $\epsilon$ is the error term. The energy producer can then hedge risks for the month by taking a position of $-b$ in energy forwards or futures and a position of $-c$ in weather forwards or futures. The relationship can also be used to analyze the effectiveness of alternative option strategies.

## 23.4 INSURANCE DERIVATIVES

When derivative contracts are used for hedging purposes, they have many of the same characteristics as insurance contracts. Both types of contracts are designed to provide protection against adverse events. It is not surprising that many insurance companies have subsidiaries that trade derivatives and that many of the activities of insurance companies are becoming very similar to those of investment banks.

Traditionally the insurance industry has hedged its exposure to catastrophic (CAT) risks such as hurricanes and earthquakes using a practice known as reinsurance. Reinsurance contracts can take a number of forms. Suppose that an insurance company has an exposure of \$100 million to earthquakes in California and wants to limit this to \$30 million. One alternative is to enter into annual reinsurance contracts that cover on a pro rata basis 70% of its exposure. If California earthquake claims in a particular year total \$50 million, the costs to the company would then be only $0.3 \times \$50$, or \$15 million. Another more popular alternative, involving lower reinsurance premiums, is to buy a series of reinsurance contracts covering what are known as *excess cost layers*. The first layer might provide indemnification for losses between \$30 million and \$40 million; the next layer might cover losses between \$40 million and \$50 million; and so on. Each reinsurance contract is known as an *excess-of-loss* reinsurance contract. The reinsurer has written a bull spread on the total losses. It is long a call option with a strike price equal to the lower end of the layer and short a call option with a strike price equal to the upper end of the layer.[6]

The principal providers of CAT reinsurance have traditionally been reinsurance companies and Lloyds syndicates (which are unlimited liability syndicates of wealthy individuals). In recent years the industry has come to the conclusion that its reinsurance needs have outstripped what can be provided from these traditional sources. It has searched for new ways in which capital markets can provide reinsurance. One of the events that caused the industry to rethink its practices was Hurricane Andrew in 1992, which caused about \$15 billion of insurance costs in Florida. This exceeded the total of relevant insurance premiums received in Florida during the previous seven years. If

[6] Reinsurance is also sometimes offered in the form of a lump sum if a certain loss level is reached. The reinsurer is then writing a cash-or-nothing binary call option on the losses.

Hurricane Andrew had hit Miami, it is estimated that insured losses would have exceeded $40 billion. Hurricane Andrew and other catastrophes have led to increases in insurance/reinsurance premiums.

Exchange-traded insurance futures contracts have been developed by the CBOT, but have not been highly successful. The over-the-counter market has come up with a number of products that are alternatives to traditional reinsurance. The most popular is a CAT bond. This is a bond issued by a subsidiary of an insurance company that pays a higher-than-normal interest rate. In exchange for the extra interest the holder of the bond agrees to provide an excess-of-cost reinsurance contract. Depending on the terms of the CAT bond, the interest or principal (or both) can be used to meet claims. In the example considered above where an insurance company wants protection for California earthquake losses between $30 million and $40 million, the insurance company could issue CAT bonds with a total principal of $10 million. In the event that the insurance company's California earthquake losses exceeded $30 million, bond holders would lose some or all of their principal. As an alternative the insurance company could cover this excess cost layer by making a much bigger bond issue where only the bondholders' interest is at risk.

CAT bonds typically give a high probability of an above-normal rate of interest and a low-probability of a high loss. Why would investors be interested in such instruments? The answer is that there are no statistically significant correlations between CAT risks and market returns.[7] CAT bonds are therefore an attractive addition to an investor's portfolio. They have no systematic risk, so that their total risk can be completely diversified away in a large portfolio. If a CAT bond's expected return is greater than the risk-free interest rate (and typically it is), it has the potential to improve risk–return trade-offs.

## SUMMARY

This chapter has shown that when there are risks to be managed, derivative markets have been very innovative in developing products to meet the needs of market participants.

In the weather derivatives market, two measures, HDD and CDD, have been developed to describe the temperature during a month. These are used to define the payoffs on both exchange-traded and over-the-counter derivatives. No doubt, as the weather derivatives market develops, we will see contracts on rainfall, snow, and similar variables become more commonplace.

In energy markets, oil derivatives have been important for some time and play a key role in helping oil producers and oil consumers manage their price risk. Natural gas and electricity derivatives are relatively new. They became important for risk management when these markets were deregulated and government monopolies discontinued.

Insurance derivatives are now beginning to be an alternative traditional reinsurance as a way for insurance companies to manage the risks of a catastrophic event such as a hurricane or an earthquake. No doubt we will see other sorts of insurance (e.g., life insurance and automobile insurance) being securitized in a similar way as this market develops.

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[7] See R. H. Litzenberger, D. R. Beaglehole, and C. E. Reynolds, "Assessing Catastrophe Reinsurance-Linked Securities as a New Asset Class," *Journal of Portfolio Management*, Winter (1996): 76–86.

Weather, energy, and insurance derivatives have the property that percentage changes in the underlying variables have negligible correlations with market returns. This means that we can value derivatives by calculating expected payoffs using historical data and then discounting the expected payoffs at the risk-free rate.

## FURTHER READING


### On Weather Derivatives

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## Questions and Problems (Answers in Solutions Manual)

23.1. What is meant by HDD and CDD?

23.2. How is a typical natural gas forward contract structured?

23.3. Distinguish between the historical data and the risk-neutral approach to valuing a derivative. Under what circumstance do they give the same answer.

23.4. Suppose that each day during July the minimum temperature is 68° Fahrenheit and the maximum temperature is 82° Fahrenheit. What is the payoff from a call option on the cumulative CDD during July with a strike of 250 and a payment rate of $5,000 per degree-day?

23.5. Why is the price of electricity more volatile than that of other energy sources?

23.6. Why is the historical data approach appropriate for pricing a weather derivatives contract and a CAT bond?

23.7. "HDD and CDD can be regarded as payoffs from options on temperature." Explain this statement.

23.8. Suppose that you have 50 years of temperature data at your disposal. Explain carefully the analyses you would carry out to value a forward contract on the cumulative CDD for a particular month.

23.9. Would you expect the volatility of the 1-year forward price of oil to be greater than or less than the volatility of the spot price? Explain your answer.

23.10. What are the characteristics of an energy source where the price has a very high volatility and a very high rate of mean reversion? Give an example of such an energy source.

23.11. How can an energy producer use derivatives markets to hedge risks?

23.12. Explain how a $5 \times 8$ option contract for May 2006 on electricity with daily exercise works. Explain how a $5 \times 8$ option contract for May 2006 on electricity with monthly exercise works. Which is worth more?

23.13. Explain how CAT bonds work.

23.14. Consider two bonds that have the same coupon, time to maturity, and price. One is a B-rated corporate bond. The other is a CAT bond. An analysis based on historical data shows that the expected losses on the two bonds in each year of their life is the same. Which bond would you advise a portfolio manager to buy and why?

## Assignment Question

23.15. An insurance company's losses of a particular type are to a reasonable approximation normally distributed with a mean of \$150 million and a standard deviation of \$50 million. (Assume no difference between losses in a risk-neutral world and losses in the real world.) The 1-year risk-free rate is 5%. Estimate the cost of the following:

(a) A contract that will pay in 1 year's time 60% of the insurance company's costs on a pro rata basis

(b) A contract that pays \$100 million in 1 year's time if losses exceed \$200 million