The Bermuda Triangle: Weather, Electricity, and Insurance Derivatives

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Deregulation of electricity markets, well under way in the United States, has created an environment of severe competition for U.S. utilities and gas producers and will probably put European utilities under the same pressure once directives on gas and electricity deregulation take effect on the Continent. The variability of revenues caused by weather conditions that utilities have faced for a long time is now augmented by the effect on earnings of new entrants into the power market.

A well-known, and important, result in the economic theory of insurance establishes that under reasonable assumptions of risk aversion, an economic agent exposed to two sources of risk, one hedgeable, the other unhedgeable, will choose higher coverage for the first risk than would have been the case if the latter did not exist. An illustration of this result is provided by the development of the weather derivatives market in the U.S. over the past two years, coinciding with the emergence of new shocks affecting the utilities revenues.

The Chicago Mercantile Exchange has just introduced standardized weather futures and options on Globex, the exchange's electronic platform. So far, weather derivatives have been sold by leading energy companies and insurance companies, mostly through the intermediation of a broker, since these options are still over-the-counter (OTC) contracts. Another type of weather-related instrument, so-called catastrophe options, were launched by the Chicago Board of Trade as early as December 1993. However, these derivatives require, like most insurance products, a demonstration of loss and an evidence of the linkage of this loss to one of nine well-defined catastrophic events (e.g., earthquakes, hail, tornadoes) triggering the property claims service (PCS) option index increments. Weather derivatives, in contrast, require no evidence of this type since the option payout is expressed in terms of a meteorological index. These bilaterally traded contracts can be combined in such a way that the risk exposure is reduced in accordance with the company's attitude toward risk.

DESCRIPTION OF THE WEATHER CONTRACTS

Many forms of weather options, such as precipitation, snowfall, or wind speed options, are available, covering a one-year or multi-year period. But the biggest volume so far has been observed on degree-days options, which are related to daily average temperatures. More precisely, cooling and heating degree-days are defined as follows:

Daily CDD = max (daily average temperature – 65° Fahrenheit, 0)

Daily HDD = max (65° Fahrenheit – daily average temperature, 0)

They are meant to represent the deviations from a benchmark temperature of 65°

Fahrenheit. Classically, a CDD (or summer) season includes months from May to September, and an HDD season, months from November to March.

Moreover, in order to represent the magnitude of the season demand for electricity dedicated to air conditioner cooling (respectively for heating gas), the aggregation effect is reflected by the following payout of the CDD option at maturity:

$$\text{CDD (T)} = \text{Nominal Amount} \times \text{on Max} \left(\sum_{t=1}^{n} \text{Max}(0, I(t) - 65) - k, 0 \right) \tag{1}$$

where n denotes the number of days in the exposure period as specified in the contract, I(t) is the average daily temperature registered at date t in the specified location, and k is the strike price of the option expressed in degrees Fahrenheit. Hence a cooling degree-day derivative is nothing but an Asian call option written on a daily CDD as the underlying source of risk.

In the same manner, the payout of a heating degree-day option at maturity is:

$$\text{HDD (T)} = \text{Nominal Amount} \; \text{Max} \left(\sum_{t=1}^{n} \text{Max}\ (0,\ 65\ - I(t)) - k, 0 \right) \tag{1a}$$

i.e., the payout of an Asian put option written on heating-degree days.

Notice that for both CDD and HDD derivatives, the option value is highly *nonlinear* with respect to the temperature index.

In the case of the option contracts introduced by the Chicago Mercantile Exchange in September 1999, the nominal amount is \$100, a relatively small number meant to create liquidity (the number of degree-days during the month of January or July may be of the order of 1,000). The final settlement price is defined by the HDD or CDD (cumulative) index of the contract month as calculated by EarthSat, and at this point the contracts exist for ten cities in the United States: Atlanta, Chicago, Cincinnati, Dallas, Des Moines, Las Vegas, New York, Philadelphia, Portland, and Tucson.

In the case of insurance derivatives, since December 1993, the Chicago Board of Trade has used the services of independent statistical firms dedicated to insurance data — Insurance Statistical Offices (ISO) in a first stage, Property Claim Services (PCS) since September 1995 — to provide the final (and also intermediate) values of the catastrophic loss indexes associated with the nine regional derivatives contracts. In the same manner, Earth Satellite Corporation (EarthSat), an international service firm, has been designated by the Chicago Mercantile Exchange to define the degree-day indexes. EarthSat has developed remote sensing and geographic information technologies, and the data it has provided over time have proven very accurate when compared with the data of the U.S. National Climatic Data Center. The Globex electronic trading platform not only allows twenty-four-hour transactions but also provides price transparency — particularly important for small investors who do not have a meteorology department within their firms.

The Chicago Mercantile Exchange trades degree-days future contracts like the degree-days options, for each calendar month. They share this feature with all electricity futures contracts traded in the United States or in Europe, a trait that has the merit of nullifying the calendar *basis risk* when hedging weather derivatives with electricity derivatives. The terminal value F(T) of a future contract at maturity is defined as

$$F(T) = \$100 \sum_j \text{[degree-days measured on day j by EarthSat]}$$

Hence F(T) will be very high if the weather conditions have been extreme during the month of analysis. And economic actors whose revenues are hurt by these extreme temperatures will hedge their risk by buying, at a date t prior to maturity, an appropriate number of futures contracts at the price F(t), hence cashing at maturity T the amount F(T) – F(t) (positive if weather conditions have been more extreme than anticipated), which will offset their operating losses.

Several other observations are in order at this point:

1. For a utility or a gas producer, the balance sheet can be managed using classic derivative contracts written on underlying equity, interest rates or exchange rates. But these instruments, as useful as they may be, do not provide protection against the business risk represented by *volumetric risk*, i.e., the uncertainty in revenues related to changes in demand for gas and

power because of weather patterns. In a situation where inventories and storage cannot be an option because of the nature of the underlying commodity, weather derivatives (or volumetric energy derivatives, as discussed below) can be structured to smooth the cash flow profile. Market players are generally reluctant to publicize transactions, because this would in particular indicate to competitors what risks they view as particularly dangerous for their earnings.

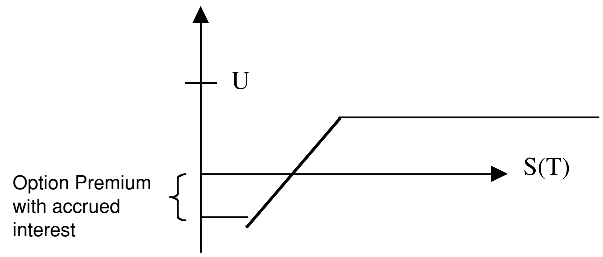
2. The fact that nearly all degree-day contracts are tied to National Weather Service data guarantees the absence of opacity and almost excludes possible manipulations of the index. These are crucial properties to the eyes of market players who may be legitimately concerned about being taken advantage of by a sophisticated counterparty. The contract sites are U.S. government sites, and the final settlement of the option occurs when the weather service publishes the official record, generally a few weeks later. Moreover, the U.S. National Climatic Data Center maintains the American archive of weather data (where historical time series can be obtained) and also provides access to the World Meteorological Organization.

The three communities carefully watching the growth of the market of weather derivatives in the U.S. are — in agreement with the pricing and hedging arguments made in this paper — power marketers, power producers, and insurance/reinsurance companies. The agricultural community is another obvious potential player but has not really been part of the transactions yet. More generally, it is estimated that 80% of all businesses are exposed to weather risk (construction companies, retail, tourism, and so forth) and that about \$1 trillion of the \$7 trillion U.S. economy is weather-sensitive.

3. In order to create a liquid market through the existence of potential buyers and sellers, the derivative contracts are often capped, i.e., the option payout is defined as the right-hand side of equation (1) as long as it is no greater than a fixed threshold U, hence limiting the option seller's exposure to this number.

Keeping in mind the algebraic gain profile at maturity of an option buyer (respectively seller), the gain profile of a capped call option (Exhibit 1) is the following at maturity:

EXHIBIT 1
Gain Profile of Capped Call Option at Maturity



We can observe that a capped call option is nothing but a *call spread* (i.e., the combination of long and short call options with different strikes). Geman [1994] emphasized that call spreads, the most popular instruments among insurance derivatives, have a gain profile identical to the purchase of an excess-of-loss reinsurance contract and hence could be valued by incorporating the insurance risk premium embedded in these XS of loss contracts into the option price. In turn, it is not surprising to find the most sophisticated (re)insurance companies in the forefront of weather derivatives transactions.

PRICING CDD AND HDD OPTIONS

This problem is probably one of the hardest yet to be solved in option pricing, the (partial) list of difficulties posed by its analysis is the following:

1. The options have an Asian-type payout, leading to more mathematical complexities than classical options. These difficulties arise from the fact that even in the fundamental reference model of a log-normal distribution for the underlying state variable S

$$\frac{dS(t)}{S(t)} = \mu dt + \sigma dW_t \tag{2}$$

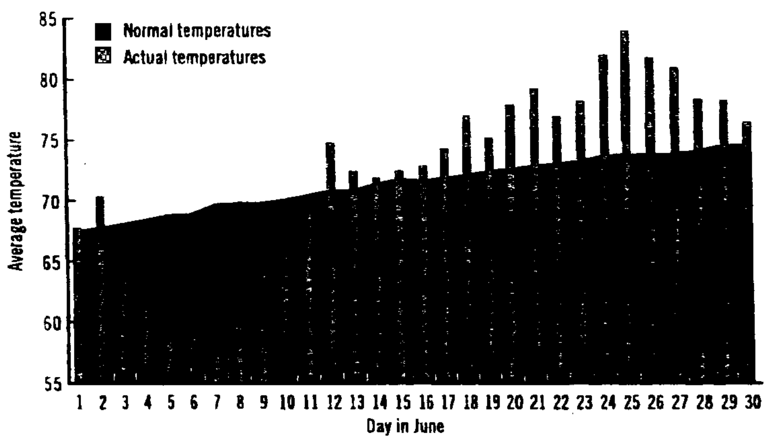
(μ and σ constants), the dynamics described by Equation (2) do not extend to a sum or an arithmetic average. Hence the Black-Scholes formula definitely does not apply, and other answers need to be found. Geman-Yor [1993] used as an intermediary mathmatical tool Bessel processes (which have the merit of being stable by additivity and of being related to the geometric Brownian motion through a time change) to obtain an *exact* analytical expression of the Laplace transform in time of the option price in the geometric Brownian motion-framework. The greeks are obtained with the same accuracy thanks to the linearity of the operators derivation and Laplace transform.

Another possible way of pricing Asian options is to use Monte-Carlo simulations. A single simulation of the index value over the whole period (0,T) provides one set of simulated daily values that, incorporated in equation (1), in turn give one *realization* of the payout of the CDD derivative. The average of these realizations over a number of Monte-Carlo simulations gives an approximation of the option price. Geman-Eydeland [1995] show that because of the smoothness of the Asian payout, a good approximation is obtained by a relatively low number of runs (e.g., 10,000); but the same accuracy for the Greeks (delta, gamma, vega) by necessity requires a higher number of simulations.

2. The evolution over the lifetime (0,T) of the option of the underlying source of risk I(t) should be properly modeled, taking into account seasonability effects over the year, stationarity of some season patterns across a period of several years, and possible changes of the parameters over time. The local warming in a city or at an airport site may be the result of global warming, the product of expanding urbanization, or even part of some secular climate cycle. Given the importance of an accurate modeling of the state variable in the option price, one must not only analyze the temperature data series available from the National Climatic Data Center but also use a survey of altessrations in the built environment. Insurance and reinsurance companies have recently systematically collected this information,

EXHIBIT 2

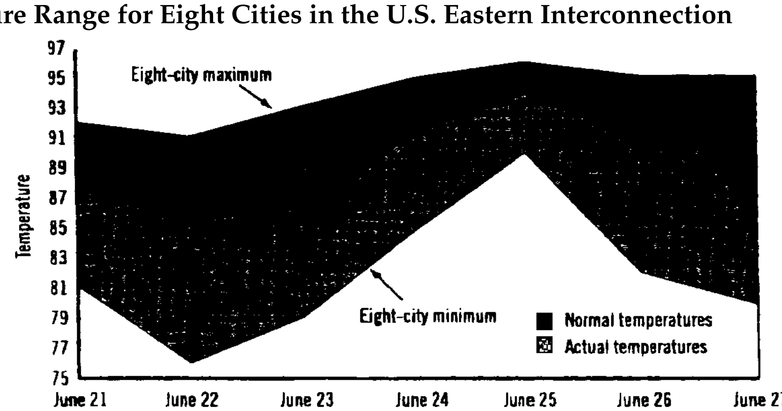
Comparison of Historical Normal Temperature and Actual Temperature



Source: National Climatic Data Center

EXHIBIT 3

Comparison of Temperature Range for Eight Cities in the U.S. Eastern Interconnection



Source: National Climatic Data Center

sometimes with the help of specialized software companies. In the U.S., government agencies represent a very rich source of information (see, for instance, Exhibits 2 and 3); in fact, all the graphs in this chapter come from publicly available data.

Let us model the temperature index as an extension of the geometric Brownian motion. Representing the randomness of the world economy by the probability space (Ω, F_t, P), where Ω denotes the set of states of nature, F_t the filtration of information available at time t and P the objective probability measure, we model the dynamics of the average daily temperature I(t) by the following stochastic differential equation:

$$dI(t) = \mu(t, I(t))dt + \sigma(t, I(t))dW_t \tag{3}$$

where

- the drift μ(t, I(t)) may be mean-reverting to capture seasonal cyclical patterns, with a level of mean-reversion possibly varying with time to translate the global warming trend.
- the volatility σ should not be constant, since there seems to be a consensus on the greater volatility of temperature over time, for a number of natural or man-made factors. However, it may be viewed admissible to take for σ either a deterministic function of time σ(t) or to choose σ stochastic — but depending only on the current level of the temperature index, i.e., a function σ(t, I(t)). In both cases, there is no other source of randomness than the Brownian motion W(t), which will avoid *incompleteness* of the weather market and non-unicity of the option price.

3. We know that the next step in the Black-Scholes-Merton proof is the construction at date t of a portfolio — to be held up to date (t + dt) and comprising one call C_t and $\partial C_t/\partial S_t$ shares. This portfolio, being riskless over the period [t, t + dt] has to provide, by no arbitrage arguments, a return equal to the risk-free rate r. This leads to the well-known partial differential equation satisfied by the call price

$$\frac{\partial C_t}{\partial t} + rS_t\frac{\partial C_t}{\partial S_t} + \frac{1}{2}\sigma^2 S_t^2 \frac{\partial^2 C_t}{\partial S_r^2} - rC_t = 0 \tag{4}$$

with the boundary condition C(T) = max(0,S(T) - k).

In the case of options on interest rates such as caps, floors, or bond options — which raise, at various levels, more difficulties than equity options — the introduction of a portfolio is still feasible, using in all cases bonds as substitutes for interest rates. In the case of weather derivatives, the same argument cannot be extended since weather is not a traded asset and there is no underlying security such as stock or a Treasury bond whose price is uniquely related to a temperature index.

4. The Feynman-Kac theorem establishes that there exists a probability measure Q defined on (Ω, F_t) — where the probability space Ω describes the set of states of nature and F_t the filtration of information available at date t — such that the solution to the partial differential Equation 3) with its boundary condition can be written as

$$C(t) = E_Q\left[e^{-r(T-t)} \max(S_T - k, 0) / F_t\right] \tag{5}$$

This probability measure Q, called risk-adjusted, allows the pricing of an option as the expectation of its terminal payout. It is obviously not equal to the statistical probability measure P, under which data are collected and its identification is generally not straightforward (its unicity is insured by "market completeness," obtained when the number of sources of randomness is no larger than the number of basic risky securities traded in the economy).

Some authors have proposed to compute the weather derivative price as the expectation (i.e., the sum of possible payouts weighted by their probabilities of occurrence) of its terminal value properly discounted and, in this order, to resort, for instance, to the Monte-Carlo simulations discussed earlier. This expectation is computed under the statistical probability measure P (meaning that the weights mentioned above do not reflect any correction for risk aversion), as if no risk premium was involved. For instance, Cao and Wei [1999] use a Lucas equilibrium framework approach to conclude that a zero market price of risk should be associated with weather derivatives values, hence justifying "the use of the risk-

EXHIBIT 4

Pennsylvania -New Jersey -Maryland Power Price versus Maximum Temperature

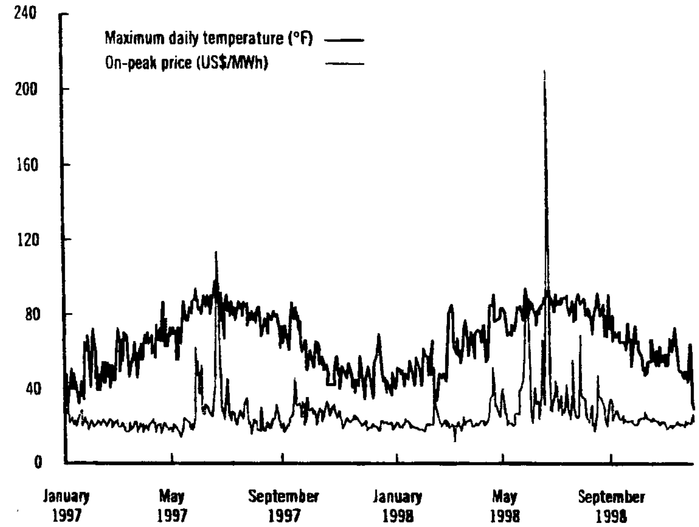


EXHIBIT 5

Palo Verde — Power Price versus Maximum Temperature

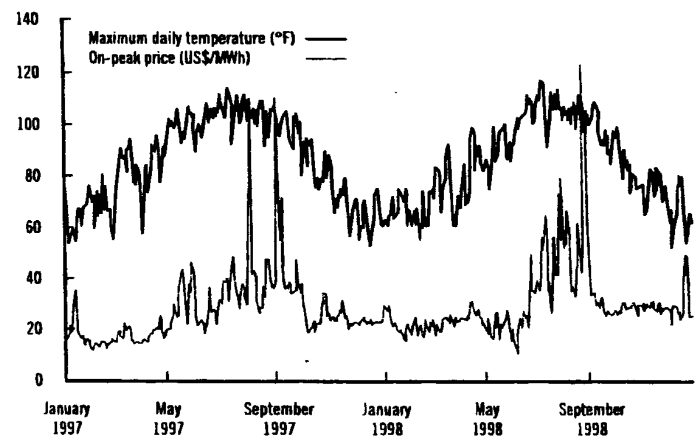
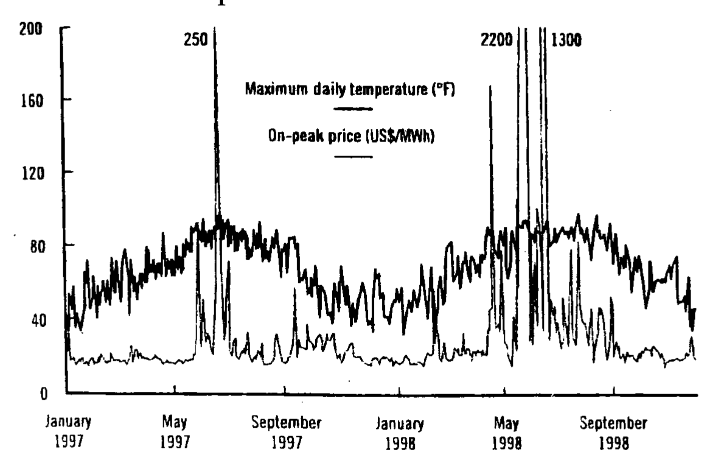


EXHIBIT 6

Cinergy Power Price versus Maximum Temperature



free rate to derive these values as many practitioners do in the industry." This assertion is *highly* questionable since weather conditions do affect the aggregated economy in a significant way. To take an extreme example, consider the Chicago heat wave of 1999, during which 130 people died. Among the many losses attached to this event, there is a loss in human capital that is clearly not offset in an economic sense, and the assumption of weather risk-neutrality of a so-called representative agent is not fully credible. As far as the weather market players are concerned, their view on the matter is clearly expressed by the large bid-ask spreads observed until lately on derivative prices (sometimes 100% of the bid price).

The difficulty of identifying a unique probability measure Q, like the impossibility of delta hedging a weather derivative or the non-existence of a hedging portfolio comprising the weather derivative and other securities and totally *riskless,* are different expressions of the same issue (which also affects credit derivatives, for instance), namely, the *incompleteness* of the weather derivatives market. This is probably one of the most important problems yet to be solved in the financial theory of derivatives (a well-known source of incompleteness that applies to all derivative markets today and is a legitimate subject of concern to practitioners is stochastic volatility).

HEDGING A SHORT POSITION IN WEATHER DERIVATIVES

The existence of a perfect hedge for a given derivative — as in the Black-Scholes-Merton [1973] model — has the merit of providing all answers at once: the price of the option, equal to the cost of the hedging portfolio and obviously the hedging strategy itself. When this exact hedge does not exist, several types of answers can be proposed.

1. The introduction of a utility function for the representative agent, which leads to identify the derivative price as the solution of an optimization problem. The shortfalls of this approach reside in the questionable identification of this utility function and assumption of the same utility for all market players.
2. The search of a so-called superhedging strategy H for the weather derivative, i.e., of a dynamically adjusted portfolio H such that at maturity

   $-C(T) + H(T) \geq 0$ in all states of the world

   Unfortunately, the cost of this strategy is in most cases outside the bid-ask prevailing in the option market and nobody will buy the option at that price.

3. Carr-Geman-Madan [1999] observe the limited validity of approaches (1) and (2) to price and hedge derivatives in incomplete markets and offer as an alternative the search for a portfolio H such that the position (– C + H) not be necessarily riskless but carry an *acceptable risk*.

When C is a weather derivative, the hedge H will certainly comprise electricity contracts-either spot or forwards and options. Since weather is the single most important external factor affecting the demand in power in the United States, one can try to represent this demand at date t for a future date t_j (see Exhibits 4, 5, and 6) as a function

$$w(t, t_j) = f\,(I(t_j), a_1, a_2, \ldots, a_n) \tag{6}$$

where

- $I(t_j)$ denotes the temperature that will be observed on day t_j at the defined site.
- $a_1, a_2, \ldots, a_n$ are parameters which may vary over time.

For instance, in the graphs (see Exhibit 7) reconstructed by Dischel [1999] using official U.S. data, the three curves associated with regions as different as southeast Wisconsin and southeast Washington have in common the property of showing a high use of residential electricity for low temperatures — below 45° Fahrenheit — and high temperatures — above 68° Fahrenheit — the range of temperatures being obviously much narrower in Florida, where it never gets very cold. Assuming that the quantity $w(t, t_j)$ can be represented as a second degree polynomial of $I(t_j)$, not taking into account the other explanatory variables of electricity demand, one or the other root of this polynomial will allow, depending on the season, to express the temperature as a function of the demand.

Following Eydeland-Geman [1998], one may represent (see Exhibits 8 and 9) the future price $F(t, t_j)$ as a function of the demand $w(t, t_j)$ and of the power stack function prevailing in the area of analysis. Using equation (5), the futures price becomes in turn a function of $I(t_j)$ and a hedge for the weather derivative can be elaborated using forward contracts. The right parts of the power stack

EXHIBIT 7
Residential Electricity Sales

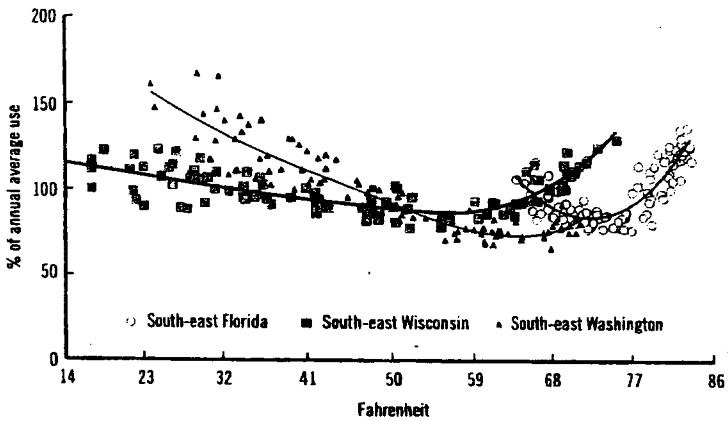


EXHIBIT 8
NPCC Generation Curve

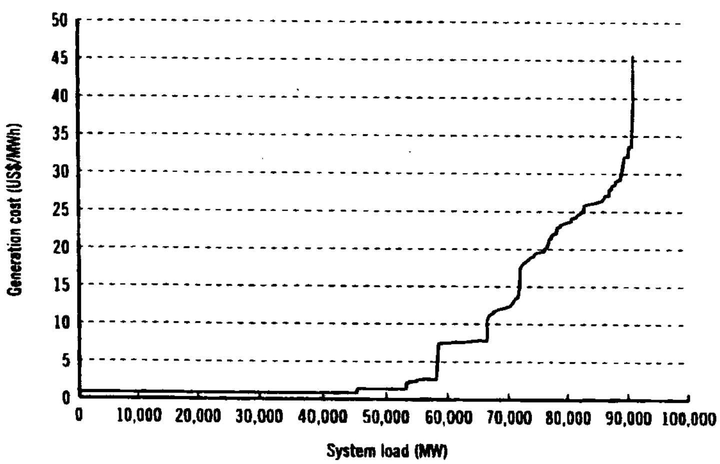
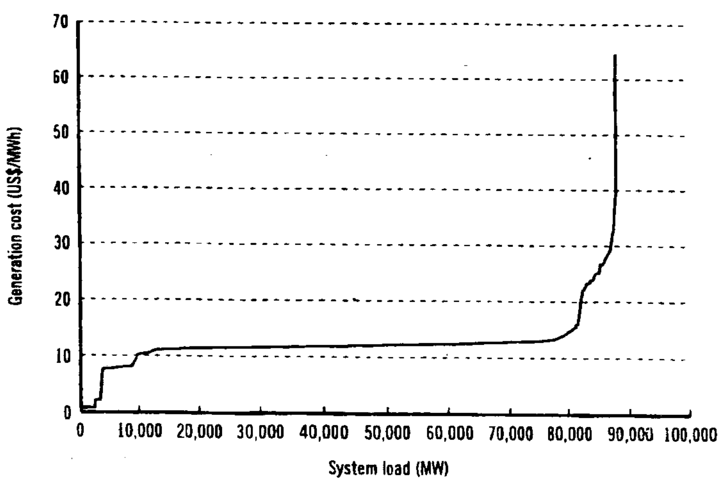


EXHIBIT 9
ECAR Generation Curve



functions 7 and 8 need to be analyzed in detail since they represent the "extreme events," hence the large payoffs of weather derivatives

Another way to proceed is to analyze the power demand as a function of temperature through its deviation to the baseload and hedge the weather derivative using volumetric or *swing* electricity options which become the right protection when temperatures rise sharply. These instruments allow to call a bigger volume of power on a number of days, chosen by the option holder, during the lifetime of the option (with constraints on the total amount and possibly, the daily amount as well).

Lastly, to manage their risk exposure, hedgers of weather derivatives may try to benefit from the diversification effect created by several positions within the same region or across different regions, in the same manner as insurance companies hedge part of their underwriting risk through portfolios of insurance contracts. In both cases, the use of insurance derivatives may protect the catastrophic risk resulting from extreme weather events.

CONCLUSION

Weather specialists are developing a variety of products (precipitation-related instruments are the next ones under scrutiny, given their relevance for hydroelectricity in particular) enabling utilities to better manage weather risk, the largest source of financial uncertainty for many energy companies and a cause of revenue risk for a large number of sectors in the economy. These products create fresh ways for banks, insurance and reinsurance companies, and energy investors to take advantage of opportunities in this burgeoning market.

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