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SPOT PRICING AND ITS RELATION TO OTHER LOAD MANAGEMENT METHODS

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The purpose of this review report is to outline the basic concepts of spot pricing and to review the background of electrical load management. For a more complete review of the literature on spot pricing, the reader is referred to the appendix to this paper. This report begins with a description of the concepts of spot pricing which, it is argued, offers the rationale for other load management techniques currently in use in the U.S. and Europe. It also can form the basis for load management tariffs such as the "Green Tariff" and time of use rates.

Instantaneous Spot Price

Since electricity is a non-storable good and its cost varies on a real time basis, the allocation of electricity generated to various uses should ideally be determined on a real time basis in order to minimize utility costs and maximize customer benefits. Indeed, the sum of customer benefits and utility savings can be maximized by economic dispatch on the generation side. On the customer side it can be maximized by consumer decisions based on an "instantaneous spot price" reflecting generating system costs and the value to consumers of electricity usage. Ignoring for the time the impact of the transmission and distribution network on generating costs (through losses, line overloads, etc.) the following relationship holds;

Instantaneous Spot Price = (1)
Incremental Operating Costs +
Quality of Supply Component.

The incremental operating cost component is related to "system lambda" used in economic dispatch but is not identical to it, since actual "system lambda" may be discontinuous or represent a signal that minimizes generating costs but does not necessarily represent system instantaneous marginal generating costs. The incremental operating cost term in relation (1) is defined as the expected change in variable system operating costs -- over the relevant unit commitment period (day or week) including costs of tie line purchases and subject to spinning reserve, ramp rate, capacity and other operating constraints -- with respect to an incremental change in system load at a particular moment.

The quality of supply component is selected so that the resulting price reflects the marginal value of expected unserved energy. In practice, the quality of supply component is subject to a ceiling consistent with the coexistence of spot and non-spot price based rates.

The instantaneous spot price definition above is effectively the instantaneous short run marginal cost. However, it might be possible to use an alternate formulation which is closer to a long run marginal cost philosophy.

Characteristics of Spot Prices

Implementation of instantaneous spot pricing is impractical because of the associated communications, transactions and metering costs. Therefore, a range of spot price based rates is considered which are related to the instantaneous spot price but are determined and posted before they come into effect. They are thus spot price based predetermined rates.

A predetermined price that maximizes the sum of customer and utility benefits is related to the instantaneous spot price as follows:

Price Determined at Time t_o to Take Effect at Time t = (2)

Expected Value of the Instantaneous Price at Time t Given the Uncertainty at Time t_o about Future Events.

In theory, an additional term should be added to this equation which depends on the nature of demand of the particular customer or customer class under the predetermined price. It may be zero, positive or negative. To a first approximation we assume here that it is zero.

There are various ways to evaluate the average value of the instantaneous spot price. One proposed means would estimate reserve margin and loss of load probability together with an a priori determined customer value of service model and an instantaneous price ceiling. The reserve margin based formula enables spot price implementation based on well defined quantities that can be verified and agreed upon by all participants: customers, utility and regulators.

The spot price market consists of price only and combined price/quantity transactions that reflect utility costs and customer needs, but differ in the level of costs and sophistication required for communication, metering, transaction implementation, decision and control actions.

The majority of present day "direct control" load management techniques can be viewed as combined price/quantity transactions. Examples include air conditioning cycling, water heating control, and Demand Subscription Service.

One example of a price only rate is today's time of use rates with a price cycle length of four months, (frequency of energy cost adjustment) and a definition of pricing periods given by seasons and time of use (peak, off-peak and partial peak periods). An example of a new type of price only transaction is a 24 hour spot price profile calcuated every day and communicated to customers a few hours before it comes into effect (for example, late afternoon to become effective at 2 AM for the following 24 hours). The cycle length in this case is one day, the definition of pricing periods is 24 hours per day and the advanced notice is a few hours.

The number of different price levels depends on the restrictions imposed on the prices that can be communicated. For example, if prices can be any level there is no restriction. On the other hand, if prices have to be selected from a finite set of, say, 3 prices (i.e., 5, 10 or 15 cents per Kwh) the number of price levels is restricted.

Restrictions on the number of price levels to be communicated impact on the communication and metering costs. The currently practiced airconditioner cycling load management program can be viewed as a two price level spot price. When the spot price increases to the higher of its two allowable levels, the utility sends a signal (communicates the higher price) resulting in load shedding. The airconditioner owner has implicitly (decided) agreed in his contract to reduce his/her electricity consumption every time the spot price assumes its high level. The utility offers an additional service to the customer by exercizing control and activating air conditioner cycling at high spot price times.

Customer Decisions and Control

Spot pricing is based on enhanced communication between the electric utility and its customers that facilitates customer action resulting in mutual benefits. Customer action consists of a decision followed by implementation. Define:

Decision: The decision of a strategy in response to available information on electricity cost, availability, etc.

Control: The implementation of a strategy consisting of consumption rescheduling, turning off or on usage devices, etc.

Two ways in which control may be exercised are:

Customer Control: Control is exercised by customer at the end use.

Utility Control: Control is exercised by the utility with decision values specified by the customer.

Price Only Transactions

Price transactions are spot price based rates that allow customers to use all the energy they desire, at the quoted price. The prices are set so that they reflect, to the extent allowed by advanced notice requirements, the actual system marginal costs and the cost to both the utility and its customers of maintaining a desired reserve margin. Table 1 exhibits the key characteristics of price transactions covering three distinct time dimensions and one "quantification detail" dimension. The level of detail adopted for each characteristic defines a particular price transaction. For example, a cycle length of four months (i.e., today's frequency of price updates established by the Energy Cost Adjustment Clause) with three pricing periods per day and three different price levels corresponds to the time of use rate schedule in effect in some utilities today. A twenty four price trajectory posted at 4:00PM to take effect on 2:00AM for the next twenty four hours is the "twenty four hour update" spot price. Similarly, a spot price posted every hour is the one hour update spot price.

Combined Price/Quantity Transactions

Price/Quantity transactions cover contracts for electricity service at lower levels of reliability. Customers, instead of seeing high prices when low reserve margins are expected, contract a priori to reduce their usage when necessary to agreed upon levels. The utility exercises the options in the contract whenever it predicts capacity shortfalls (generation or transmission) or unacceptably small reserve margins. In terms of decisions and control, customers under a price/quantity transaction contract make decisions regarding consumption ceilings conditional upon certain events (capacity shortfall severities, etc.).

TABLE 1

Key Characteristics of Price Only Transactions

Characteristics	Examples
Length of Price Cycle (Cycle Length)	1 year, 1 month, 1 day, 5 min.
Definition of Pricing Periods Within Cycles (Period Definition)	1 per year, 3 per day, 24 per day
Number of Different Price Levels (Number of Levels)	2, 3, Continuous
Advance Posting of Prices (Advance Notice)	1 month, 1 week, 10 hours, none
Number of Quantities	KwH only, KwH and KW

Many load management programs presently undertaken by U.S. utilities recently evaluated by PG&E and SCE (in fact all except time of use rates) fall under the price/quantity transaction type. Water heater control and airconditioning cycling are combined price/quantity transaction contracts with utility exercised control and a particular end use being the quantity controlled. The Demand Subscription Service (DSS), Group Load Curtailment (GLC) and COOP programs are price/quantity contracts with KW being the quantity controlled.

The principles for establishing the customer incentives for adopting price/quantity price contracts are to achieve (to the extent allowed by the particular characteristics of the contract) customer behavior as close as possible to what it would have been under spot pricing. Thus, customers receive incentives, (discounts, penalties, etc.) that tend to equalize on the average the marginal benefit the customer receives from his/her electricity usage to the marginal cost of providing it. This allows customers to minimize their costs while reducing utility costs as well.

Under certain conditions of customer incentives, a price/quantity transaction can become "equivalent" to a price only transaction. One example is when:

- Customer's incentive for adopting a price/quantity contract is a reduced energy charge calculated as the expected spot price conditioned on the critical event not occurring.

- Customer's incentive for honoring the price/quantity contract is a monetary penalty calculated to yield what the customer "should" have paid under a spot price calculated after the critical event occurred.

Comparison of Price Only with Price/Quantity

Price-only transactions simplify the marketplace interactions between the utility and its customers. Simplicity and ease of understanding are thought to be key components of success of any marketplace structure. Many of the desirable properties of combined price/quantity transactions can also be obtained with price only. Hence, price only transactions are viewed as the key component of spot price based transactions. However, price/quantity can have an important role.

Potential advantages of combined price/quantity transactions include:

- Lower metering, communication (transactions) costs
- Allowing additional degrees of freedom in rate choices
- Simplification of customer's control problems by allowing utility to exercise control

o Providing utility with more certainty regarding customer response.

These four potential advantages are discussed below.

Certain types of combined price/quantity transactions (such as direct appliance control and Demand Subscription Service) yield low metering and communication costs. The main advantage in this area (over say, a two level price only transaction) is that the price only transaction requires some sort of metering of energy consumption during both levels.

The second potential advantage of additional degrees of freedom could be particularly valuable for less detailed spot price based rates with long cycles (month or longer) and only a few pricing period definitions (three per day or less). In such cases, the average value of the instantaneous spot price is not always adequate to elicit system wide cost-minimizing behavior since the correlation between customer demand and the instantaneous spot price may be non-zero. However, the recommended price only transactions which appear most implementable limit long cycle lengths to residential customers. Thus, this advantage of price/quantity transactions would not be applicable to medium and large customers. Its usefulness for residential customers is questionable considering the relatively high costs involved in estimating the correct parameters of a complex rate.

The third potential advantage of combined price/quantity transactions (customer convenience) can also be realized by price only transactions with a utility provided customer control service. However, the transactions costs of metering and communication can be higher with the price only approach. This could be a real advantage for combined price/quantity especially when fast customer response (say, seconds to minutes) is wanted to deal with system operating problems such as the need to carry sufficient spinning reserve.

The fourth potential advantage of combined price/quantity involves increased certainty of customer response. The validity of this argument is subject to debate as issues can be presented on both sides. For example, direct control of a particular appliance at first seems to be more certain than indirect control via prices. However, predicting response to direct appliance control requires detailed modeling of an explicit appliance's usage pattern as a function of time of day, season, and weather (direct control only works when the appliance is on). Predicting response to a price only rate which applies to all of a customer's usage requires a more aggregate level of modeling and hence, can be more certain.

More research is needed before the relative roles of price only and combined price/quantity transactions are well understood. However, based on our present understanding, we feel that:

- o Price only, 24 hour or 1 hour update transactions are to be preferred for large industrial or commercial customers when 1 hour is the shortest time interval of concern.

- o Combined price/quantity transactions may have advantages for small residential customers.

- o Combined price/quantity transactions may have advantages when handling power system phenomena appreciably faster than one hour.

Requirements for Long Term Forecasts

Long term forecasts of spot prices are provided to customers to aid them in making investments. These long term rate forecasts are analogous to long-term load forecasts and are as predictable as future yearly load duration curves and variable generation costs are predictable today.

Operational decisions by customers depend on medium term rate forecasts which can be obtained reliably in a fashion analogous to daily or weekly load and variable generation cost forecasts used today by utility unit commitment planning.

Control actions which are analogous to generation control in today's utility functions, require repeated and short term response to the spot price based rates. The control action which implements customer operational decisions can be carried out by either the customer or by the utility following customer prespecified instructions. Utility exercised control can relieve the customer from the task of constantly responding to price changes if so desired.

Customer Options

A range of spot price based rates with different characteristics may coexist. Thus the issue of which particular customers see which particular rate is important. The general criterion is that this matching be based on a tradeoff of hardware, communication, metering and other transaction costs versus the sum of utility and customer benefits. Benefits increase the closer the rate tracks "the instantaneous spot price". But communication and metering costs also increase. When rates characterized by long price cycles (i.e., one month or longer) and/or an aggregate pricing period definition (i.e., 3 periods per day or less) are considered, cross subsidy issues may arise.

A basic question is voluntary (by the customer) versus mandatory (by the utility or regulatory agency) rate selection. A general recommendation is that a basic minimum cycle length and detail of price period definition for each customer class (and possibly size, etc.) should be prescribed by the utility and the regulatory agency on the basis of cost benefit and cross-subsidy considerations. However, a customer should have the option to move to a rate with a smaller cycle length for a finer period definition as long as the customer is willing to incur the additional transaction costs.

Customer Generation

Spot price based rates can prove very useful in incorporating customer generation into the utility system. Customer generation (i.e. cogeneration and small generators) must, according to the PURPA regulations, be purchased by the electric utilities at "full avoided cost". Avoided cost calculations and especially the energy versus capacity credit issue have presented formidable challenges for both the utilities and the regulatory commissions.

Spot price based rates can provide a consistent way to credit customers for electricity fed into the grid and satisfy PURPA regulations. The relationship of the spot price to marginal costs and avoided costs is discussed further elsewhere (see appendix). It is worthwhile, however, to stress here the significance of using the spot price to credit customer generation in eliciting cost minimizing operational decisions. Customer generation earns more at times of high utility incremental operating costs or capacity shortages. Therefore, customers are motivated to generate more at times when their generation is most valuable to the utility and thus schedule their operation and maintenance according to overall utility system cost minimization criteria.

Summary Discussion of Spot Pricing Concepts

There are many types of spot priced based transactions that may be implemented to increase utility and customer benefits. In most cases, offering customers a menu of transaction types rather than a single transaction type is desired. The combination of characteristics that are desirable may vary widely from utility to utility and depends on the costs and benefits involved. The particular needs and capabilities of customers and the utility as well as the communications, metering, control and transactions costs associated with a particular implementation determine its desirability.

Spot pricing is an extension and formalization of the marginal cost of service studies presented to public utility commissions over the last decade. Spot pricing can be viewed as extending the utilities' optimum generating dispatch logics to include the customers. Spot pricing can be considered as the logical evolution of present day load management techniques. Hence, spot pricing is not a radically new, revolutionary concept.

APPENDIX:

SPOT PRICING LITERATURE REVIEW AND REFERENCES

APPENDIX

A-1

SPOT PRICING LITERATURE REVIEW AND REFERENCES

This Appendix provides a discussion of the available literature related to spot pricing. The appendix itself has been adapted from Bohn [1982].

B.1 General Background

The idea of setting electricity prices on a spot price basis is quite old. It has been used for sales between utilities in the U.S. under the name "economy interchange." Pricing methods containing elements of spot pricing have been implemented for sales to customers on a limited basis by a number of utilities in the U.S. and Europe.

- Sweden has a complex rate structure for its largest industrial customers which contains many provisions analogous to spot pricing [Camm, 1980].

- Great Britain adds a price surcharge during periods of anticipated supply shortfalls, or "peak period warnings." This rate is applied to several hundred large customers [Mitchell, Manning and Acton, 1979].

- San Diego Gas and Electric Company calculates a demand charge for its 23 largest customers based on their demand at the time of system peak. This can be interpreted as a spot price [Bohn 1980, Gorzelnik, 1979].

- Florida has a power broker system which systematically communicates energy prices between utilities at individual bus points in the Florida grid system. This is spot pricing with spatial (transmission) differentiation between utilities in the system [Cohen, 1982].

The desirability of time of use rates has been the topic of major research by the Electric Power Research Institute [1979]. For a good summary of this effort and discussions of associated problems, see Malko and Faruqui [1980] and Faruqui and Malko [1981a]. For a good review of the U.S. Department of Energy sponsored residential time of use experiments, see Faruqui and Malko [1981b].

Although rates which are effectively spot prices have been in use for some time, the academic literature on spot pricing theory for electricity is less well developed. There is, however, a rich literature on optimal pricing and generation planning for electricity, but it emphasizes predetermined prices ("time-of-day" pricing), or direct utility load control ("load management").

The idea of time differentiated prices goes back at least to Boiteux [1949] (see also Vickrey [1955] and Steiner [1957]). Until Brown and Johnson [1969] the models were purely static and deterministic. During the 1970's various authors presented prescriptions for time-of-use pricing in static models with demand uncertainty. Their analysis can be considerably simplified and generalized by using the concept of spot pricing.

B.2 Time of Use Pricing

The "standard" time-of-use pricing models are surveyed in Gellerson and Grosskopf [1980] and Crew and Kleindorfer [1979]. They include Wenders [1976], Crew and Kleindorfer [1976, 1979 Ch. 4 and 5], Turvey and Anderson [1977, Ch. 14], and various predecessors. These models include multiple types of generators and stochastic demand. Some of the limitations of these models are as follows:

- Generating unit availability is practically ignored or modeled by simply derating unit sizes at all times. This fails to penalize properly large units, and it gives wrong estimates of the probability that rationing will be needed. It also gives no guidance for how to evaluate new technologies such as solar and cogeneration, whose "availabilities" are correlated with demands.

- There is no analysis of how or when prices should be recalculated. These models rule out frequent recalculations (by spot pricing) by assumption. By assuming infinitely repetitive demand cycles and stable factor prices they show no need for annual or less frequent recalculations.

- These models treat all investment as occurring at once. Investment is really a sequential process. True utilities never have the static optimal capital stock of these models, because conditions change more rapidly than capital stock turns over. Therefore pricing equations which assume optimal capital stock, i.e. assume that short run and long run marginal costs are equal, have limited practical value. In fact long run marginal costs can only be calculated conditional on a particular scenario or probability distribution of demand and factor prices. This problem is addressed by Ellis [1981].

- The models assume that demands and generating costs are independent from one hour to another. This is very convenient, since it allows the use of a single load duration curve (or price duration curve). Nonetheless the availability of storage [Nguyen, 1976] or demand rescheduling can have a major impact on optimal prices and investment policies.

- The models ignore transmission, which is equivalent to assuming an infinitely strong transmission system. This is not feasible when setting practical rates for power buybacks, but these models give no insight into how to price over space. Current debates about "wheeling tariffs" indicate the importance of this issue when trying to encourage independent generation by firms located in the territory of a monopolistic utility.

- The models do not use the device of state contingent prices. Therefore, the investment conditions derived in the models are hard to interpret, although they are correct (given the limiting assumptions above). For example, Crew and Kleindorfer [1979, p. 77] interpret their results only for the case of interchanging units which are adjacent in the loading order. Littlechild [1972] showed the way out of this problem, but his point was apparently missed by subsequent authors.

B.3 Dynamic Pricing/Investment Models

Several authors present deterministic explicitly dynamic models which can be interpreted as deterministic versions of spot pricing. Crew and Kleindorfer [1979, Ch. 7] give a continuous time optimal control model with one type of capital. They get the result that:

> Whatever the level of capacity, price is to be set to maximize instantaneous [short run] welfare returns subject to the given capacity restriction. [p 113] [That is,] price should equal SRMC. Of course, at optimum capital stock is adjusted so as to equate SRMC and LRMC....In the event of .... a fall in demand, [optimal] price is less than LRMC, then capacity would be allowed to decline until equality between price and LRMC were re-established.

They are thinking here on a time scale of years, not hours; they reject continuous adjustment of prices to reflect the actual level of demand. Nonetheless, their model can be interpreted in terms of hourly price adjustments.

Turvey and Anderson [1978, Ch. 17] have a discrete time dynamic model which leads to discontinuous prices, as capital investment is made in lumps. However they reject this approach: "It is apparent that, for one reason or another, such fluctuations are unacceptable." They also acknowledge that investment decisions must be made before price decisions, and with more uncertainty about future demands, but they do not incorporate this into their models [p. 305].

Ellis [1981] explicitly models sequential investment and pricing decisions. He concludes that "...welfare optimal pricing rules differ according to whether prices must be set either before or after investment decisions are made." [p. 2] He uses dynamic programming to look at how the character of optimal sequential investment depends on capital stock irreversibility and the sequential revelation of information about future demands.

B.4 Spatial Pricing

Several previous authors have studied how public utility prices should vary over space. Relevant models include Takayama and Judge [1971] (which was not directed at electricity), Craven [1974], Dansby [1980], Scherer [1976, 1977], and Schuler and Hobbs [1981]. All of these models are deterministic and most are static.

Scherer has the best model of electricity line losses and line constraints, and includes T&D investment options. Scherer's approach is to use a mixed integer programming model of an electricity generation and transmission network. In his model spatially distinct prices appear as dual variables on demand at each point in the network. In his numerical case study he found that prices between different points at the same time varied by up to 30 percent. The absolute and percentage variations across space changed over time. [1977, p. 265] He does not discuss these results, but presumably they reflect the different losses resulting from different optimal load flows at each level of total system demand.

Much of Takayama and Judge concerns pricing across space. They consider only competitive markets, but use an explicit optimization method of finding equilibrium, so their analysis is equally applicable to a welfare maximizing monopolist. They assume a constant transport cost per unit between two points, no transport capacity limit, and no losses. This makes their models more appropriate for conventional commodities than for public utility products such as electricity. They also assume linear demand and supply functions. But their framework does provide insights into more general spatial and temporal pricing problems. For example they discuss "no arbitrage" conditions which bound the price differences between different locations.[1971, p 405] Their models do not include capital, so they provide no insights into optimal investments in transport facilities.

B.5 Pricing of Reliability

One way to view spot pricing is that it allows customers to choose their own reliability levels. Marchand [1974] has a model in which customers select and pay for different reliability. The utility allocates shortages accordingly, when curtailment is necessary. His approach differs from (and is, except for transactions costs, inferior to) spot pricing because customers must contract in advance, and therefore have no real time control over their level of service. Also, customers not curtailed by the utility have no incentive to adjust demands.

A simple version of Marchand's proposal is in use in the U.S. and elsewhere. Called "direct load control", it involves the utility turning off specific equipment of the customer's. Despite its increasing use [Morgan and Talukdar, 1979; Gorzelnik, 1982] optimal pricing and use of direct load control has not been extensively studied by economists. (Note, however, Berg [1981] and Dams [1979].)

B.6 Spot Pricing

Spot pricing of public utility services was apparently first proposed by Vickrey, under the name "responsive pricing". His original article [1971] presented a general discussion using as examples mainly long distance telephones and airlines. The emphasis is on curtailment premia, rather than on marginal production cost changes over time. Later manuscripts on electricity develop the ideas in more detail, including some discussion of optimal investment criteria [Vickrey, 1978 p 12], metering requirements and designs, pricing of reactive energy, and short run marginal operating costs (system lambda). He proposes that utilities be free to set prices however they want over time, subject only to limits on total profits.

Vickrey's essential insight was that prices can be set after some random variables are observed, and optimal prices should reflect this. Since his original article different versions of this basic idea have been developed independently and under different names, with varying levels of rigor. These include:

- "State preference" approach to pricing electricity [Littlechild, 1972], a formal stochastic model of both pricing and investment under static conditions. Both operating costs and capacity constraints are modeled, but with homogeneous fixed coefficient technology, i.e., only one kind of capital.

- "Time varying congestion tolls" for a highway or communications network. [Agnew, 1973; 1977] A formal deterministic optimal control model incorporating only capacity constraints and delays. No discussion of investment.

- "Spot pricing" of electricity. [Schweppe, 1978; Schweppe et al. 1980, 1978; Bohn et al., 1981; Caramanis et al. 1982, Bohn 1982].

- o "Real time pricing" of electricity. [Rand, 1979] Informal; no specific proposal.

- o "Load adaptive pricing" of electricity. [Luh et al, 1982] A game theoretic model; nonlinear prices allowed. Quadratic production costs assumed, with no capacity constraints and no investment. Their formulation allows for games between one utility and one consumer which is not a pure price taker.

- o "Flexible pricing" of electricity. [Kepner and Reinbergs, 1980] Informal.

Many other authors have explicitly rejected the idea that prices can be set after events are revealed. For example, Crew and Kleindorfer [1980, p 55] write: "For the case of the regulator setting the price ex post, he or she would either have to allow a market-clearing price or have some deliberate arrangement for setting the price above or below the market clearing price. Were the regulator [to allow] the market clearing price, he would, in effect, be giving up his right to regulate price." Turvey and Anderson [1977, p 298] are even more adamant in their rejection of spot pricing:

> ...for a wide class of random disturbances (but not for all), it is not possible to respond to the resultant random excess or shortage of capacity by adjusting prices. Failure of a generating plant on Thursday cannot be followed by a higher price on Friday, and the price in January cannot be raised when it becomes apparent that January is colder than usual. Even though telecontrol makes the necessary metering technically possible, it would be expensive, and... there would be difficulties in informing consumers of the new price. It would also be scarcely possible to estimate its market clearing level. Sudden and random price fluctuations would in any case impose considerable costs and irritations on consumers. Hence responsive pricing that always restraints demand to capacity is not practical, and some interruptions are thus desirable.

Their rejection thus appears to be based on the belief that the transactions costs of spot pricing would outweigh any possible benefits.

A series of articles on spot pricing and Interactive Load Control appeared in Electric Review in 1981 and 1982 [Berrie, 1981/82].

The Credit and Load Management System (CALMS) is an important system and hardware development in England [Peddie, 1982a, 1982b] which has major implications for spot pricing. The key component, the Credit and Load Management Unit (CALMU) is a microprocessor-based metering control and display system designed for residential use. A new version presently being designed can accept a spot price data stream. It is closely related to the Universal Metering and Control System (UMACS) discussed in Chapter III.

Chemical Week [Sept. 29, 1982, pp. 66-67] discusses spot pricing from the chemical industry customer's point of view. This article mentions other spot pricing efforts under way in Europe.

Finally, there are the most recent articles from MIT on spot pricing [Bohn, 1982; Bohn et al, 1981] which show the structural advantages of spot pricing, and Caramanis [1982] which evaluates the investment implications of spot pricing. An analysis of spot pricing in Wisconsin [Caramanis, Tabors et al., 1982] showed the customer and utility benefits given operation of a single utility.

Extensions of Spot Pricing ideas into broader utility issues such as Deregulation have also been carried out by the MIT group [Bohn et al., 1981; Golub et al., 1982, Bohn et al., 1982. These analyses have discussed the structural use of full spot pricing for deregulation of generation which includes both the customer and the utility working within an energy marketplace.

B.7 Annotated List of MIT Reports, Papers

Many reports and papers have been written at MIT that are related to spot pricing. The following is an annotated list. Many of the following were discussed above but the list provides a self-contained description of available MIT efforts. Spot pricing is one part of a larger overall approach to electric power systems called Homeostatic Control, so there are many references to Homeostatic Control.

The list is separated into three areas

- Spot pricing and Homeostatic Control
- Work on customer demand modeling related to spot pricing.
- Approaches to deregulation based on spot pricing.

The following cover spot pricing and Homeostatic Control:

"Power Systems 2000" by Fred C. Schweppe, IEEE Spectrum, Volume 15, Number 7, July 1978. 6 pages. An informal discussion of how a decentralized state-of-the-art power system could work using spot pricing.

"New Electric Utility Management and Control Systems: Proceedings of Conference" by the Homeostatic Control Study

Group, June 1979, 200 pages, MIT-EL 79-024. Discussion papers and audience reaction from a conference on homeostatic control.

"Industrial Repsonse to Spot Electricity Prices: Some Empirical Evidence," by R. Bohn, February 1980, MIT-EL-80-016WP, 30 pages. An econometric examination of 3 industrial customers in the U.S. which are on a weak form of spot pricing. Detailed statistics, but no discussion of what customers did to allow them to respond.

"Homeostatic Utility Control", by F. Schweppe, R. Tabors, J. Kirtley, H. Outhred, F. Pickel and A. Cox, IEEE PAS-99 No. 3, May/June 1980, 9 pages. A complete and relatively concise presentation of homeostatic control's main elements. A few equations, but no formal derivations.

"Quality of Supply Pricing for Electric Power Systems" by H. Outhred and F.C. Schweppe, IEEE Summer Power Meeting, July 1980, paper A80 084-4, 5 pages. An intuitive exploration of the quality of supply aspects of spot pricing. No equations. Following reference develops the same concepts rigorously.

"Optimal Spot Pricing of Electricity: Theory" by R. Bohn, M. Caramanis and F. Schweppe, March 1981, MIT-EL 81-008WP, 100 pages. Formally derives optimal spot prices and optimal investment under spot pricing. Mentions some regulatory issues but does not discuss them. Many equations; no numerical examples.

"Optimal Spot Pricing: Practice and "Theory," IEEE PAS Vol. PAS 101 No. 9, Sept. 1982, by M. Caramanis, R. Bohn and F. Schweppe, 12 pages. A paper based on above reference written for engineering audience.

"Investment Decisions and Long-Term Planning Under Electricity Spot Pricing," by M. Caramanis, IEEE PAS, Vol. PAS 101 No. 12, Dec. 1982, 9 pages. More details and extension of above in investment areas.

"Utility Spot Pricing Study: Wisconsin," by M. Caramanis, R. Tabors and R. Stevenson, MIT Energy Laboratory, June 1982, 200 pages. A case study simulating benefits and their distribution associated with spot pricing of industrial customers in a Wisconsin, U.S. utility.

"Spot Pricing of Public Utility Services," by Roger Bohn, unpublished PhD thesis, MIT, Sloan School of Management, Cambridge, May 1982. Also Technical Report MIT-EL 82-031, 200 pages. A general and comprehensive treatment of economic issues related to spot pricing of public utility services including investment and operational issues, from the utility, societal, and customer perspectives. A generic customer response model/framework is also developed.

"Homeostatic Control for Electric Power Usage," by F. Schweppe, R. Tabors and J. Kirtley, IEEE Spectrum, July 1982, pp. 44-48 (5 pages). An informal discussion of how Homeostatic Control and spot pricing works.

"Optimal Pricing of Public Utility Services Sold Through Networks," by R. Bohn, M. Caramanis and F. Schweppe, Graduate School of Business, Harvard University, HBS 83-21, 97 pages). Detailed discussion on impact of transmission distribution networks in spatial dependence of spot prices. Discusses properties of optimal wheeling charges.

Customer demand and value of service modeling is crucial to the spot pricing concept. Many of the following do not address explicitly spot pricing but contribute to the development of a solid foundation for physically based, end use modeling.

"Space Conditioning Load Under Spot or Time of Day pricing," by P. O'Rourke and F. Schweppe, IEEE PAS, forthcoming, 1982 Summer Power Meeting, 9 pages. Develops simple to use formulae to evaluate savings-discomfort trade-offs for space conditioning under spot pricing.

"A Theoretical Analysis of Customer Response to Rapidly Changing Electricity Prices", by R. Bohn, 1980, revised January 1981, MIT-EL-81-001WP, 150 pages. A series of models of electricity use, emphasizing the response of profit-maximizing customers to spot prices. Derives the increase in customer profits from various forms of spot pricing. Some discussion of actual case studies, but no real-life numerical examples.

"A Weather Dependent Probabilistic Model for Short Term Load Forecasting," by F. Galiana and F. Schweppe, IEEE PAS Winter Power Meeting, N.Y., (C72-171-2), 1972, 7 pages. Discusses an hour by hour 1 week forecasting model of aggregate demand for use in operational control centers.

Electric Load Modeling by James Woodard, Garland Press, N.Y., 1979, 350 pages. Provides a deterministic framework for physically based end use modeling of electrical demand with emphasis on the residential sector.

"Physically Based Load Modeling" by Y. Manichaikul, J. Woodard, and F. Schweppe, 1978 IEEE Summer Power Meeting, paper No. F78 518-3, 8 pages. Provides a stochastic framework for end use modeling.

"Physically Based Industrial Electric Load" by Y. Manichaikul and F. Schweppe, IEEE Trans. on Power Apparatus and Systems, Vol. PAS-99, No. 2, March/April 1980, 7 pages. Application of the stochastic framework to the industrial sector by individual case studies of seven specific customers.

"Physical/Economic Analysis of Industrial Demand" by Y. Manichaikul and F.C. Schweppe, IEEE Transactions on Power Apparatus and Systems (PAS) Volume PAS 99, Number 2, March/April 1980, 7 pages. Models loads as random processes. Does not explicitly model effect of changes in electric rates, but suggests how to estimate these effects. Based on seven specific case studies.

"Physically Based Modeling of Cold Load Pickup" by S. Ihara and F. Schweppe, IEEE Trans. on Power Apparatus and Systems, Vol. PAS-100, No. 9, September 1981, 9 pages. Application of stochastic strutures to modeling load level response to short interruptions.

"Electric Load Management by Consumers Facing a Variable Price of Electricity" by P. Constantopoulos, R.C. Larson and F. Schweppe, 1982 Joint National Meeting, San Diego, California, October 26, 1982, 30 pages. General discussion of a theoretical framework for analyzing customer response to spot prices.

Spot pricing and Homeostatic Control were developed for regulated utilities. However, the ideas provide a sound basis for partial or full deregulation of electric utilities if that is desired. The following are articles focusing on the deregulation area.

"Deregulating the Electric Utility Induustry," by R. Bohn et al. [1981], MIT Energy Laboratory Technical Report MIT-EL 82-003.

"Using Spot Pricing to Partially Deregulate Utilities, Customers and Generators," by R. Bohn, F. Schweppe and M. Caramanis, Presented at the NARUC Conference, Columbus, Ohio, Sept. 10, 1982, 11 pages.

"An Approach for Deregulating the Generation of Electricity" by B. Golub et al., forthcoming in Electric Power Strategic Issues: Deregulation and Diversification, edited by S. Plummer, T. Ferrar and W. Hughes.

B.8 References

Agnew, Carson E. [1973] "The Dynamic Control of Congestion-Prone Systems Through Pricing", Ph.D. dissertation, Stanford University.

Agnew, Carson E. [1977] "The Theory of Congestion Tolls", Journal of Regional Science, Vol. 17, No. 3, pp 381-393.

Baumol, W.J. and Bradford, "Optimal Departures from Marginal Cost Pricing," American Economic Review, 60 (June 1970): 265-283.

Berg, Sanford V. [1981] "Load Management: Rationing Versus Peak Load Pricing", The Energy Journal, Vol. 2, No. 1, pp 89-98.

Berrie, T., "Interactive Load Control, Parts 1 to 6," Electrical Review, 1981/1982, England.

Bohn, Roger. "Spot Pricing of Public Utility Services," Unpublished Ph.D. Thesis, MIT, Sloan School of Management, Cambridge, May 1982. Also Technical Report MIT-EL 82-031.

Bohn, Caramanis and Schweppe [1981], "Optimal Spot Pricing of Electricity: Theory," MIT-EL 81-008WP.

Bohn, R. E., R. D. Tabors, B. W. Golub, F. C. Schweppe [1982] "Deregulating the Electric Utility Industry", MIT Energy Laboratory Technical Report MIT-EL-82-003.

Bohn, Roger E. [1980] "Industrial Response to Spot Electricity Prices: Some Empirical Evidence", MIT Energy Laboratory Working Paper MIT-EL-80-016WP, February 1980.

Bohn, R., Schweppe, F., Caramanis, M. [1982] "Using Spot Pricing to Partially Deregulate Utilities, Customers and Generators", presented at the NARUC Conference, Columbus, Ohio, Sept. 10, 1982.

Bohn, R., Caramanis, M., Schweppe, F. "Optimal Pricing of Public Utility Services Sold Through Networks." Graduate School of Business, Harvard Universty, HBS 83-31.

Boiteux, M. [1949] "La tarification des demandes en point: application de la theorie de la vente au cout marginal", Revue Generale de l'electricite, Vol. 58, pp 321-340.

Brown, Jr., G. and M. B. Johnson [1969] "Public Utility Pricing and Output Under Risk", American Economic Review, Vol. 59, March 1969, pp 119-129.

Camm, Frank [1980] Industrial Use of Cogeneration Under Marginal Cost Electricity Pricing in Sweden, RAND report WD-827-EPRI.

Caramanis, M., Bohn, R., and Schweppe, F. [1982], "Optimal Spot Pricing: Practice and Theory," IEEE Transactions on PAS. September 1982.

Caramanis, Tabors, and Stevenson, "Utility Spot Pricing: Wisconsin," MIT Energy Laboratory Report, MIT-EL-82-025, June 1982.

Caramanis, Michael, "Investment Decision and Long-Term Planning under Electricity Spot Pricing," IEEE Transactions on PAS, December 1982.

Coase, Ronald H., "The Marginal Cost Controversy," Economica 13 (1946): 169-182.

Coase, Ronald H., "The Theory of Public Utility Pricing and Its Application," Bell Journal of Economics and Management Science, 1 (Spring 1970): 123-128.

Cohen, "A Spot Market for Electricity: Preliminary Analysis of the Florida Energy Broker," Rand Report N-1918-DOE, February, 1982.

Constantopoulos, P., Larson, R.C., Schweppe, F. [1982] "Electric Load Management by Consumers Facing a Variable Price of Electricity," 1982 Joint National Meeting, San Diego, California, October 26, 1982, p. 164.

Craven, John [1974] "Space-Time Pricing for Public Utilities", The Bell Journal of Economics and Management Science, Vol. 5, pp 187-195.

Crew, M. A. and P. R. Kleindorfer [1976] "Peak Load Pricing with a Diverse Technology", The Bell Journal of Economics, Spring 1976, pp 207-231.

Crew, M. A. and P. R. Kleindorfer [1979] Public-Utility Economics, St. Martins Press, NY.

Crew, M. A. and P. R. Kleindorfer [1980] "Public-Utility Regulation and Reliability with Applications to Electric Utilities", in M. A. Crew, 1980.

Dansby, Robert E. [1979] "Multi-Period Pricing with Stochastic Demand", Journal of Econometrics, Vol. 9, pp 223-237.

Dansby, Robert E. [1980] "Spatial Considerations in Public Utility Pricing", in Michael Crew, Issues in Public-Utility Pricing and Regulation, Lexington Books, Lexington, Mass.

Davidson, C.O. and Dent, D.J., "Efficient Pricing of Electric Energy: A State of the Art Conference." Montreal, Canada (May 14, 1978): 181-198.

Electric Power Research Institute, Electric Utility Rate Design Study, 1979.

Ellis, Randall P. [1981] "Electric Utility Pricing and Investment Decisions Under Uncertainty", PhD dissertation, Massachusetts Institute of Technology.

Faruqui, Ahmad and Malko, Robert, "Load Shape Modifications Associated with Time of Use Rates for Electricity," in Hotelling, ed., Challenges for Public Utility Regulation for the 1980s, MSU Press, 1981a.

Faruqui, Ahmad, and Malko, Robert, "Respponse of Residential Electric Loads to Time of Use Pricing: Evidence from Eleven

Pricing Experiments," Midwest Economic Association, 45th Annual Meeting, 1981b.

Galiana, F. and Schweppe, F., "A Weather Dependent Probabilistic Model for Short Term Load Forecasting," IEEE PAS Winter Power Meeting, N.Y., (C72 171-2), 1972.

Gellerson, Mark W. and Shawna P. Grosskopf [1980] "Public Utility Pricing, Investment, and Reliability Under Uncertainty: a Review", Public Finance Quarterly, Vol. 8, pp 477-492.

Golub, B., Tabors, R., Bohn, R. Schweppe, "An Approach for Deregulating the Generation of Electricity," in Electric Power Strategic Issues: Deregulation and Diversification," Edited by Plummer, J., Ferrar, T., and Hughes, W.

Gorzelnik, Eugene F. [1979] "T-O-U rates cut peak 3.5%, kWh by 1.3%", Electrical World, September 15, 1979, pp 138-139.

Gorzelnik, Eugene F. [1982] "Special Report: Utilities Embrace Direct Load Control", Electrical World, February 1982, pp 69-84.

Hotelling, H., "The General Welfare in Relation to Problems of Taxation and of Railway and Utility Rates," Econometrica 6 (July 1938): 242-269.

ICF [1980]. "Interruptible Electric Service for Industrial and Large Power Customers," prepared for North Carolina Utilities Commission under Contract No. 04-90228. May 1980.

Ihara, S., Schweppe, F. [1981] "Physically Based Modeling of Cold Load Pickup," IEEE Trans. on Power Apparatus and Systems, Vol. PAS-100, No. 9, Sept. 1981, pp. 4142-4150.

Kepner, John and Reinbergs, M. [1980] "Pricing Policies for Reliability and Investment in Electricity Supply as an Alternative to Traditional Reserve Margins and Shortage Cost Estimations," unpublished manuscript.

Littlechild, Stephen C. [1972] "A State Preference Approach to Public Utility Pricing and Output Under Risk", The Bell Journal of Economics and Management Science, Vol. 3, pp 340-345.

Luh, Peter B., Yu-Chi Ho and Ramal Muralidharan [1982] "Load Adaptive Pricing: An Emerging Tool for Electric Utilities", IEEE Transactions on Automatic Control, April 1982.

Malko, Robert, and Faruqui, Ahmad, "Implementing Time of Day Pricing of Electricity: Some Current Challenges and Activities." in M. Crew, ed., Issues in Public Utility Pricing and Regulation, Lexington, 1980.

Manichaikul, Y. and F.C. Schweppe, "Physical/Economic Analysis of Industrial Demand," IEEE Transactions on Power Apparatus and Systems, Volume PAS-99, No. 2, March 1980.

Manichaikul, Y., Woodard, J., Schweppe, F. [1978] "Physically Based Load Modeling," 1978 IEEE Summer Power Meeting, paper No. F78 518-3.

Marchand, M. G. [1974] "Pricing Power Supplied on an Interruptible Basis", European Economic Review, pp 263-274.

Mitchell, Bridger M., W. Manning and J.P. Acton [1979] Peak Load Pricing: European Lessons for U. S. Energy Policy, Berllinger Publishing Co., Cambridge, Mass.

Morgan, M. Granger and Sarosh N. Talukdar [1979] "Electric Powerr Load Management: Some Technical, Economic, Regulatory and Social Issues", Proceedings of the IEEE, Vol. 67, No. 2, February, 1979, pp 241-313.

Nguyen, D. T. [1976] "The Problem of Peak Loads and Inventories", Bell Journal of Economics, Vol. 7, Spring 1976, pp 197-206.

O'Rourke, P. and Schweppe, F., "Space Conditioning Load under Spot or Time-of-Day Pricing," IEEE Transactions on PAS, 1982.

Outhred, H. and F.C. Schweppe, "Quality of Supply Pricing for Electric Power Systems," IEEE Transactions on PAS, 1981.

Peddie, R.A. et al. [1982a], "A Credit and Load Management System--Design Considerations," August 1982, South Eastern Electricity Board, East Sussex, England.

Peddie, R.A. et al. [1982b], "Customer/Utility Relationships. A New Approach to Credit and Load Management Systems," August 1982, South Eastern Electricity Board, East Sussex, England.

RAND [1979] "Real Time Pricing and the Future of the Electricity Industry", Unpublished memo (by Derek McKay?), October 1979.

Ramsey, F., "A Contribution to the Theory of Taxation," Economic Journal, 37 (March 1927): 47-61.

Scherer, Charles R. [1976] "Estimating Peak and Off-Peak Marginal Costs for an Electric Power System: An Ex-Ante Approach", The Bell Journal of Economics and Management Science, Vol 7, Autumn 1976, pp 575-601.

Scherer, Charles R. [1977] Estimating Electric Power System Marginal Costs, North Holland Publishing Co, Amsterdam.

Schuler, Richard E. and Benjamin F. Hobbs [1981] "The Consequences of Alternative Organizations of the Electric Utility Industry", Presented at 1981 Annual Meeting, American Economic Association.

Schweppe, F. [1978] "Power Systems 2000", IEEE Spectrum, July 1978.

Schweppe, F. et al [1980] "Homeostatic Utility Control", IEEE Transactions on Power Apparatus and Systems, Vol. PAS-99, No. 3, May/June 1980.

Schweppe, F.C., Tabors, R.D., Kirtley, J.L., "Homeostatic Control for Electric Power Usage," IEEE Spectrum, July 1982, pp. 44-48.

Steiner, Peter O. [1957] "Peak Loads and Efficient Pricing" Quarterly Journal of Economics, Vol. 71, pp 585-610.

Takayama, Takashi and George Judge [1971] Spatial and Temporal Price and Allocation Models, North Holland Publishing Company, Amsterdam.

Turvey, Ralph and Dennis Anderson [1977] Electricity Economics, Johns Hopkins University Press, Baltimore.

Vickrey, William [1955] "Some Implications of Marginal Cost Pricing for Public Utilities", Papers and Proceedings of the American Economic Review, Vol. 45, pp 605-620.

Vickrey, William [1971] "Responsive Pricing of Public Utility Services", Bell Journal of Economics and Management Science, Vol. 2, No. 1, pp 337-346.

Vickrey, William [1978] "Efficient Pricing Under Regulation: The Case of Responsive Pricing as a Substitute for Interruptible Power Contracts", unpublished manuscript, Columbia University.

Wenders, J. T. [1976] "Peak Load Pricing in the Electricity Industry", The Bell Journal of Economics, Vol. 7, pp 232-241.