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MIT-EL--81-033

DE82 013658

HOMEOSTATIC CONTROL:

THE UTILITY/CUSTOMER MARKETPLACE FOR ELECTRIC POWER

Fred C. Schweppe
Richard D. Tabors
James L. Kirtley

MIT Energy Laboratory Report MIT-EL 81-033
September 1981

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I. THE SETTING

The present electric utility environment is exemplified by uncertainties in demand, in fuel and operating costs, and, significantly in capital costs and finance. From a time only a few years ago in which load growth increased evenly at between 3 and 10% annually, load growth is now less certain and variable between 1 and 3% annually for many utilities in the United States. The result of this uncertainty in demand growth has been to make long-term capacity planning increasingly difficult. Some electric utilities have found themselves with excess capacity (though possibly of the wrong fuel type), others with insufficient capacity. These capacity short and longfalls have largely had the same result; unhappy customers, and in most instances unhappy regulatory bodies attempting to respond to pressures both from customers and from the utilities themselves.

The second significant source of uncertainty for the utilities is in the area of fuel costs and availability. Many utilities switched from "dirty" fuels such as coal to the cleaner fuels of oil and natural gas in the late '60s and early '70s only to find in 1973 that the fuel that might be the cleanest was uncertain both in its price and in its availability. For regions such as the Northeast and the North Central which are heavily dependent upon foreign oil imports this has meant that their price for electrical power has risen far more rapidly than has been the case for other regions with, say, large hydro resources. The result has been an increase in the price ratio between the most expensive state to the least expensive state of a factor of over 6 in average cost to a residential consumer. The price fluctuations and uncertainties in availability have had an additional unsettling impact on the utilities and their customers. They have introduced the concept of the monthly fuel adjustment charge, which reflects the real cost of generation either during the immediately preceding month or the average of the preceding two to four months. The result has been an increased awareness on the part of both industrial and residential customers of one of the realities of electrical power--it costs more to generate during certain seasons of the year than during others. The presence or absence of a single nuclear generating facility from a system can be worth a 5-second clip on the evening news and a shift of several cents in the fuel adjustment charge. The presence of rapidly changing fuel costs and uncertain sources of supply have added greatly to the planning woes of the electric power industry.

The third major source of uncertainty facing the utility industry is increased capital and financing costs. The rapid oil increases of the '70s have been felt throughout the economic structure of the U.S. where double-digit inflation and prime interest rates near 20% have become the norm. This has affected utility ability to raise capital and to obtain bonding for long term capital projects. Given the current inflation rate, the estimated cost of common building materials in a major construction project such as a nuclear or coal-fired plant, which takes between 8 and 12 years to build, will have doubled after the first seven years. Hence, additional trips to the capital market prior to completion of the project are often required.

It is not possible to complete a discussion of the uncertainties associated with the current utility environment without mention of the influence of regulators on both day-to-day operations and on the structure of the utility industry in the decades ahead. New federal legislation such as the Public Utility Regulatory Policy Act (PL 95-617) has had, and will continue to have, a major impact on utilities. Regulations on fuel use, energy conservation, and environmental impacts have significantly adjusted the utility's operating strategies. Regulation concerning the operation and licensing of nuclear power plants have greatly influenced the availability of new generating facilities--particularly since Three Mile Island.

In summary, the utility environment has inherently changed over the last decade. Uncertainty is now a significant component of daily operations and planning. To look back with some sense of longing to the relatively simpler environment of the past may be academically interesting but is certainly not productive. This paper looks to the future.

While there has been a major negative impact during the '70s from increased inflation and increased uncertainties in the utility environment, the '70s brought to the utility industry, as they did to virtually every facet of the economy, a near revolution in computational and communications capability. The development of the integrated circuit and its proliferation into intelligent machinery has given the utility industry an increased ability to control its own operations as well as to potentially control customer loads. In addition, the increase in communications capability has meant that the utility, which formerly communicated with even its largest customers only through a monthly bill, is now technically able to communicate with customers in real time much as it already does with other utilities and between its own plants and dispatchers.

Examples of the use of intelligent control and advanced communications equipment abound both in industrial facilities and within utilities themselves. Energy price increases of the past decade have made the need to monitor and control overall energy use in many manufacturing facilities a major money-saving proposition and a microprocessor-based industry has arisen to meet these needs. The utilities have also been able to benefit from the increased availability of both microprocessing and efficient communication facilities. The modern dispatch center is a sophisticated computer facility with sensing and computational facilities at individual substations and commúncations in real time between facilities to monitor, adjust and react in emergency situations. The future described in this paper involves the expansion of this computational and communication capability to further integration of the utilities and their customers.

Load management offers a means of adjustment on the part of the utility and its customers to uncertainty in supplies and prices and to uncertainties in system operations. It also takes advantage in some instances, of the revolution in microprocessing and communications. Today there are two major categories of load management schemes, those that are direct or physical, and those that are indirect or economic.

Direct load control is characterized by an on/off switch whose action is generally initiated by the utility itself. Examples of direct-load control devices range from time clocks attached to hot water heaters to highly sophisticated signaling to devices which use customer-specified priority logic to limit the kW demand of a specific facility. Within the range of devices lies a myriad whose purpose is to allow the utility to remove--generally as rapidly as possible--all or a portion of a customer's load on the basis that the customer receives a reduction in the overall bill in some fashion. This method of load management appears to provide the utility with a "direct" control but, in practice, the actual response can only be estimated statisically as the utility does not know which devices are actually being used at a given time. One of its disadvantages is that increased utilization of such control causes customers to either refuse to accept it or try methods to circumvent it. A major disadvantage is that the control actions are initiated with no knowledge of customer priorities, needs or costs at a given time.

The second type of load management considered here is indirect or economic management. There have been a number of experiments and now there are a considerable number of utilities for which at least a portion of customer loads are on some form of time-of-use or time-of-day rate. This allows for some level of customer efficiency in deciding the amount of electricity that will be consumed at a given time. However, it has the disadvantage of not being sensitive to uncertainties such as plant outages, short-term weather effects, and coal strikes. Thus it does not account for the actual marginal cost of energy.

Despite their shortcomings, however, direct and indirect load management methods have become significant concepts considered by most utilities. Their use has emphasized the willingness and need for the utility and the customer to communicate.

The concepts which follow in this paper are built upon the knowledge that the utility of the future will be a new-breed utility whose environment will be far more uncertain but whose management options will be far greater based largely on computation and communications capabilities. The following concepts build heavily upon knowledge of the existing and evolving utility industry; upon the revolution in computation and communication, and upon the efforts to date in both direct and indirect load management. The concepts may appear to be revolutionary but are actually evolutionary. They blend many various ideas into a complete package, combining computation and communication with utility operations in real time. Most significantly, they combine the customer and the utility into a single system--a marketplace--in which both can enter, trade, and benefit. The marketplace retains the good features of present-day load management techniques while simultaneously removing most of their disadvantages.

II. THE RESPONSE

Our response to the problems of today's utilities is called Homeostatic Control. Homeostastic Control is founded on two major principles:

- Feedback Between Customer and Utility
- Customer Independence

It is to the advantage of both the customer and the utility that the electric power system be planned and operated as economically and physically efficiently as possible subject to constraints on environmental quality and on system integrity. Historically, this has been the sole task of the utility. Customers have rarely received direct feedback from the utility concerning the overall cost of operation and maintenance of the system integrity. Hence, customers have had little opportunity to adapt their behavior to utility needs. Utilities have rarely received direct feedback from customers concerning the type of service and reliability the customers would really like to buy. This lack of feedback results in higher costs for both the utility and the customer. Homeostatic Control provides the missing feedback.

At the same time that it is important to have a close interaction between customers and the utility, it is equally important for customers to make independent decisions. It is more efficient for a customer to make the decision to reschedule or even to shed load than it is for an external source, such as an electric utility controller, to make the decision to manage or shed customer load. Industrial customers are far more able to judge the value of electricity to their processes at any given point in time than is the utility controller who has little, if any, information concerning the process. From the utility's point of view, it is important not to be forced into the politically dangerous position of having to play the "big brother" who decides how and when customers are going to use their processes, appliances, or other usage devices. Under Homeostatic Control the utility does not "cross the meter line" and the customer retains complete freedom of decision making.

Homeostatic Control achieves the two principles of feedback and independence using the concepts of an energy marketplace. The energy marketplace is a practical reality because of the major revolution taking place in microelectronic communications and control.

The structure of the overall energy marketplace is illustrated in Figure 1. The "Marketplace Controller" consists of human-computer teams and communication systems that control, operate, and maintain the security of the overall power system, establish prices, and conduct certain transactions. The Marketplace Controller performs all of the functions of present energy control centers, distribution control centers, etc., plus additional functions resulting from the marketplace

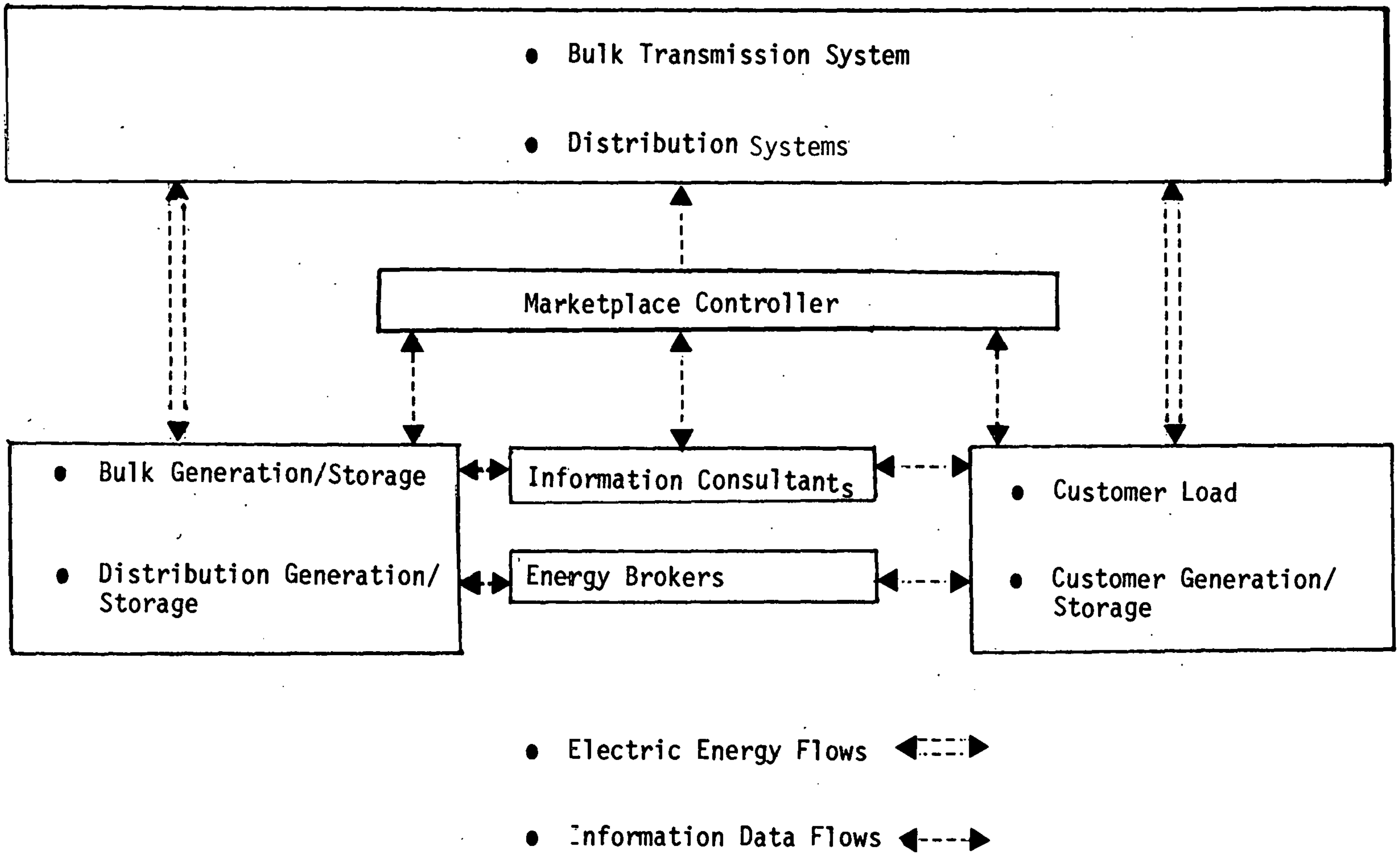

Figure 1. The Energy Marketplace

itself. Information Consultants provide forecasts of future price behavior and/or recommendations for action. Energy Brokers buy and sell long-term contracts for electric energy. These brokers provide a futures (commodity) market in electric energy. A deeper understanding of the individual roles will develop as the discussion proceeds. A key actor in the overall energy marketplace not shown in Figure 1 is the regulatory commission.

An energy marketplace can have different types of transactions taking place. Transactions can involve real energy, reactive energy, and various measures of dynamic behavior over time. Transactions can include different types of price-quantity relationships with price-quantity links ranging from complete prespecification to open marketplace devices. Time intervals between price changes and decisions can range from years to seconds or less.

The following discussion does not attempt to cover the full spectrum of all possible marketplace transactions and control actions. Instead the discussions concentrate on selected particular concepts involving "energy pricing" and "dynamics pricing."

II.1 Energy Pricing

The two quantities of concern under energy pricing are the amount of real energy (kilowatt hours) and reactive energy (kilovar hours) used or generated. Two types of associated transactions are spot pricing and utility-customer contracts.

Spot pricing is a concept in which the price of electricity varies in response to the cost of supply and supply-demand conditions. Rates are computed by the Marketplace Controller and transmitted to the customers in any one of several ways. Two examples of spot prices are:

- 5-Minute Update: Spot prices (buy and sell, real and reactive) are recomputed every 5 minutes based partly on existing utility economic dispatch optimization programs which track system fuel costs in real time. Communication is done in real time over any of several electronic links.
- 24-Hour Update: Spot prices (buy and sell) are precomputed once a day for each hour of the next day, based partly on utility unit commitment logics which forecast the next day's cost. Communication of the 24 numbers is achieved by newspaper publication and by providing customers with a telephone number to dial if they prefer.

Obviously, these two examples only illustrate the range of possibilities.

Spot prices are determined by consideration of:

- Economics: Cost of fuel, capital, maintenance, etc.
- Quality of Supply: Present and expected future voltage, frequency, and availability of power.

If, for example, total demand is approaching total available generation, quality of supply considerations could increase spot buy and sell prices beyond that indicated by direct utility expenditures to reflect the extra pricing forces needed to prevent system collapse. A "socially optimum" pricing theory encompassing all costs (utility, and customer) has been developed which automatically covers both economics and quality of supply. This theory is summarized in terms of "An Optimum Spot Pricing Theorem" in Figure 2. Spot pricing eliminates block rates, demand charges, ratchet clauses, hours use charges, and penalties charged for back-up power except as justified by cost of transformer-distribution line hardware.

Customers respond to changing spot prices by adapting service requirements that are reschedulable or nonessential. Customers respond to forecasts of future spot price behavior as well as the current spot price. Customers who have their own generation consider forecasts of both buy and sell prices. Such forecasts are either self-generated or are obtained from the Information Consultants.

In addition to spot prices, prespecified contracts involving real and reactive energy options of various types can exist. Two main categories of contracts are:

- Customer Exercised Options: Customer purchases options to buy or sell energy in the future from the Energy Brokers.
- Marketplace Exercised Options: Marketplace Controller purchases options to exercise control over generation and load now and in the future.

Customer Exercised options involve long-term contracts with Energy Brokers ranging in duration from days to years which give the customers rights to buy or sell some quantity or range of quantitites of energy with some time dependent restrictions for some prespecified explicit range of prices. Such long term contracts can provide insurance to those customers who feel a special need; albeit at a higher average price. They also allow customers to speculate in the long-term market if they so desire.

In an ideal world, where spot prices are established and communicated instantaneously and where customers always respond in their own best interest, pricing would be the only tool the Marketplace Controller would need to ensure satisfactory marketplace operations, in both economic and

AN OPTIMUM SPOT PRICING THEOREM

Figure 2

- IF
  - Generation-transmission-distribution outages, weather, and customer desire are exogenous random variables
  - Decisions on real and reactive energy generated and used by each participant are constrained by
    - Individual device capacities
    - (Total generation) - (Total Usage) - (Losses) = 0
    - Network Constraints
      - Line Flows
      - Voltage Magnitudes
  - Criterion of optimality is to maximize

Global Social Welfare = Value to User - Cost of Fuel for Generation - Investment Cost
- Generation
- Network
- Usage

- THEN
  - Optimum behavior results if each individual participant maximizes own welfare given a spot price for energy (real and reactive) set by:

Spot Price = Marginal Fuel Costs + Quality of Supply + Losses

  - Quality of Supply is not zero if
    - Insufficient generation is available
    - Network constraints are active
  - Spot prices are equal for generation and usage

COROLLARIES

- Optimum spot price involves
  - No demand charges
  - No capacity credits-debits
  - No backup charges
  - No ratchet clauses

- Generation investment costs are met from marginal fuel profits plus generation quality of supply prices

- Network operating and investment costs are met from

Net Marketplace Revenue = Total Money Paid by all Users - Total Money Paid to all Generators

where the net marketplace revenues come from loss revenues plus network quality of supply.

- Optimal spot pricing automatically leads to optimal dispatching by generating plants, without a need for central dispatching.

engineering senses. However, ideal worlds only exist in the classroom. Marketplace Controller exercised options adjust to the real world. Marketplace Controller exercised options usually involve short-term contracts with durations ranging from seconds to hours. Microshedding is an especially important concept which falls into this category.

Microshedding solves the dilemma of how the utility can have the direct load control that is often desirable without crossing the meter line. Microshedding can be viewed as a method for customers to buy the particular mix of firm and non-firm (microsheddable) energy that fits their needs. Under microshedding the utility and the customer negotiate a contract for quantity control under which the customer will reduce energy consumption to a prespecified level at the option of the Marketplace Controller. The customer chooses, a priori, the level of firm energy desired and, when called upon, specificies what operations will be shed or rescheduled. Microshedding is an interruptible rate that is renegotiated as frequently as every few minutes or as infrequently as annually. The important concept is that the customer chooses what will be affected, the utility determines when. For customers who are also under spot pricing, microshedding contracts cover energy usages only up to the time of the next spot price update.

In the near term at least, many customers will not see rapidly updated spot prices and will not be involved in microshedding. This means that the Marketplace Controller may have to exercise direct rationing controls. In theory, if there are both spot and non-spot customers and if there is a generation shortage, the spot price should be raised only to a certain level, after which it becomes socially optimal to ration the non-spot customers by subjecting them to rotating blackouts. By analogy with the different types of spot prices, two examples of rationing are the 5-minute warning rationing and the 24-hour warning rationing.

II.2 Dynamics Pricing

Electric power systems are built to provide real electric energy to customer usage devices. However, the nature of the physical system leads to spot prices for reactive energy. In a similar fashion, it may be desirable to have marketplace transactions on quantities which affect the dynamic nature and behavior of the physical system.

Two basic categories of "dynamics pricing" are

- o Time Response Pricing: Economic incentives are based on the explicit time history of a customer's response to a particular situation.
- o Dynamic Characteristic Pricing: Economic incentives are based on a customer's general behavior characteristics.

One example of "time response pricing" is to pay customers extra during emergency conditions when system frequency is deviating significantly from 60 Hz if they decrease demand when frequency is low and increase demand when frequency is high. An example of "dynamic characteristic pricing" is to charge customers extra if their equipment tends to cause low amplitude, lightly dampened power system oscillations. Another example is to charge customers whose equipment generates harmonics.

For customers with their own generators, dynamics pricing is a way to motivate them economically to install governors, voltage regulators, etc., which help the power system's dynamic behavior.* However, even

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*An alternative to dynamics pricing is the use of standards. This is theoretically less efficient but obviously must be considered.

customers with only demand can participate actively by exploiting the fact that many electric loads are energy rather than power loads.

Energy loads require that an average rather than an instantaneous condition be met. This includes such loads as space conditioning and melt pots, as opposed to rotating machinery, lights, and computers. Energy loads may be rescheduled for seconds to minutes to improve power system behavior without affecting the customer's needs. For such load control to be effective, two types of information are required:

- A locally measured signal(s) indicates how the customer desire for service is being fulfilled. For example, is the temperature of the building being maintained within desired limits? Is the water level of a tank being maintained between desired limits?
- One or several locally measured or provided signals such as frequency, voltage, or power flows which provide information on overall power system dynamic behavior.

The Frequency Adaptive Power Energy Rescheduler (FAPER) is a device which illustrates these concepts and which has been built in our laboratory. This device is based on a small microprocessor which accepts a temperature or water level measurement, measures local frequency, and then takes the appropriate action.

In the previously mentioned ideal world of instantaneous spot pricing and perfect customer response, dynamics pricing and spot pricing become the same thing in many, if not all, areas. Dynamics pricing has been discussed separately because Homeostatic Control is intended for the real world.

III. Questions of Regulation

The discussions so far have ignored questions associated with utility organizational structure and regulation such as

- Which parts of the marketplace are natural monopolies which should be under jurisdiction of a regulatory commission?
- How are the spot pricing rules used by the Marketplace Controller specified?

In order to address such questions, several organizational strategies for the energy marketplace of Figure 1 are discussed.

III.1 Today: Regulation

First, consider an organizational structure based directly on today's vertically integrated and regulated utilities. All of the different elements of Figure 1 except the "customers" would be part of the single regulated utility. This regulated utility would own the bulk generation, transmission and distribution networks; would operate the Marketplace Controller; and would provide Information Consultant and Energy Brokerage services for customers.

With Homeostatic Control implemented under this structure, the regulatory commission would be responsible for setting the rules and formulae which the Marketplace Controller uses to compute spot prices, etc.. At first this seems to be a radical departure from present practice where the regulatory commission sets the actual rates themselves. However, if one takes the point of view that, under the present system, the regulatory commission sets the rates using the formulae that (revenue) = (costs) + (reasonable rate of return), then the concept of the Marketplace Controller computing the actual rates (spot prices) is not a major departure. The regulatory commission is still controlling the equations; they are just being solved a lot faster, in almost real time.

If spot prices are computed using the optimal spot pricing theorem of Figure 2, the regulated utility may receive either too much or too little revenue relative to its allowed rate of return. The regulatory commission would decide how to resolve the problem by use of refunds or surcharges . Many possibilities exist. The prime constraint is that the refunding or surcharging mechanism minimize any undesirable modifications in customer behavior.

Under this regulated structure, customers could still own their own generation as they wish. Such generators would not be regulated and customers might make windfall profits or go bankrupt depending on whether they are clever, lucky, or unlucky. One of the major benefits of Homeostatic Control is that it provides a climate under which customer-owned generation can be installed under honest economic conditions.

III.2 A Possible Tomorrow: Deregulation

One logical extension of unregulated customer generation is deregulation of all generation. In a similar vein, many separate unregulated companies, independent of the utility, could provide Information Consultant and Energy Brokerage services. Hence, one possible future would consist of:

- Regulated Utility:
    - Transmission and Distribution Network
    - Marketplace Controller

- Free Enterprise Marketplace Participants
    - Customers with
        - only load
        - only generation
        - both generation and load
    - Information Consultants
    - Energy Brokers

In such a situation all generation is deregulated. With this structure, the regulatory commission would regulate the transmission, distribution and marketplace controller parts of the overall system but would only monitor the behavior of the other participants to insure that collusion did not occur.

With deregulated generation, the price of electricity would be determined primarily by marketplace forces. New power plants might be built using venture capital by groups of individuals or organizations who felt they had the right technology to meet their predictions of future need. If their predictions were correct, they would make a profit as the spot price for their product would exceed their capital and fuel costs. If their prediction of needs and/or choice of technology were badly in error, they would lose money and perhaps go bankrupt.

Completely deregulated generation is one possible tomorrow. What about deregulating transmission and distribution? The optimum spot pricing theory allows participants to build a line and to buy energy at one point in the region and sell it at another. Participants will make money if their transmission or distribution line is better than the regulated utility's network. However in practice, complete deregulation of the transmission distribution network seems impractical because of the difficulty, for example, of preventing any one participant from gaining monopoly power over a geographic area. A related organizational question is: Should transmision and distribution systems be separated? Relative to the concepts and theory underlying Homeostatic Control, there is no theoretical advantage in such separation, and yet there is no reason it cannot occur. After all, the transmission and distribution systems can simply view each other as buying and selling partners which, in fact, occurs today in many areas. Thus the question of whether to have local coop distribution systems is entirely a matter of local option, financing, etc. In a similar fashion the size of a regulated transmission and distribution utility should be just large enough to be efficient relative to human, computer, and capital resources. There is no technical or economic need to have a single, national transmission and/or distribution utility.

There is a tendency to think of possible organizational structures in terms of economic issues and spot pricing. However, it is important to remember that power system engineering considerations such as system security and dynamic response characteristics are at least as important and must be dealt with effectively before any structure can evolve. It is with these power systems engineering aspects that the Homeostatic Control concepts such as microshedding and dynamics pricing play crucial roles.

The desirability of deregulated generation requires many detailed studies as deregulation has many practical shortcomings as well as theoretical and practical values. We have not done such studies. However, when considering the nature of the problems facing both the customers and utilities, we feel that such studies involving alternate organizational structures should be done soon. Homeostatic Control does not require nor necessarily imply deregulated generation; Homeostatic Control does, on the other hand, make deregulated generation possible.

IV. Is It Practical?

A common initial reaction to Homeostatic Control is, "Is it practical in the real world?" The paragraphs which follow address the implementation issues associated with the various parts of the marketplace of Figure 1. They offer answers to one way of implementing Homeostatic Control. We suspect there are many others.

IV.1 Marketplace Controller

The Marketplace Controller is responsible for many presently performed power system control and operation functions which will not be discussed here. Most of the new marketplace functions are based on present functions. For example, if both 5 Minute Update Spot Price and 24 Hour Update Spot Price are being used, these prices will be computed using present economic dispatch and unit commitment techniques combined with demand models, similar to those in use today, but modified to accept prices as exogenous variables. Of course, if all generation is deregulated, the Marketplace Controller will let the marketplace compute the prices. The process of contracting with customers for options (microshedding and/or generation reserves) which the Marketplace Controller can exercise is little more than a variation on the present utility energy control center practice of buying energy options from neighboring utilities. The extra flexibility and control ability provided by such options will result in modification of certain normal emergency state control logics. None of this is trivial, but all can be achieved by evolving existing, proven methodologies.

IV.2 Information Consultants and Energy Brokers

With a marketplace structure based on today's utility system organization, the regulated utility itself would provide the Information Consultant and Energy Brokerage services. Since conversion to spot pricing will not take place instantly for everyone, there will be time to obtain and analyze the data necessary to enable development of good models for forecasting future prices and for forming rational brokerage policies. Much of the existing demand modeling methodology can be used as a foundation.

Alternatively, the evolution of independent companies offering Information Consultant and Energy Brokerage services to marketplace customers could take place naturally. Many small companies might start to offer services and then the natural pruning process of competition would reduce the numbers to a relative few in which the public has confidence. Even when all utility generation is regulated, Information Consultants and Energy Brokers that are independent of the regulated utility may be desired.

IV.3 Utility Customer Communication and Interface

The Energy Marketplace cannot function without communcations between its different parts. The nature of the needed communication links depends on the types of transactions. There is a big difference in the communication link needed for an industrial user to talk with an energy broker and a Marketplace Controller to communicate emergency state signals to customers. Fortunately, a broad spectrum of communication media is presently available and many others are under development or testing. Existing communication systems such as newspapers and commercial broadcasts could give price forecasts as they now give weather forecasts. A variety of different techniques for using power lines or utility operated radio systems as communication media are now in competition. Existing telephone lines can be used in the usual way (the customer dials the Marketplace Controller) or by superimposing signals which do not interfere with normal telepone operations. Use of satellites as communcation vehicles is also under active consideration.

It is necessary to consider very carefully the interface between the customer and utility domains. That interface, in addition to transmitting electrical energy between the utility and the customer, must provide an energy usage measurement and recording system of some sort and perhaps a communications interface. Since one of the basic principles of Homeostatic Control is customer independence, the utility should have no control over devices and no direct access to any devices which store information within the customer's domain. The communications interface can ensure this by providing a buffer: information flowing across this interface would always be "sent" by one party or the other.

As an example of a simple interface, a 24 Hour Updated Spot Price needs only a recording watt meter which stores the hourly energy flows (postive or negative) for a month. The meter is then read by the meter person who physically takes the 24 x 30 numbers back to the office where the month's bill is computed by multiplying by the spot price. Such recording meters are already commercially available. An electronic communication interface is not needed because the customer learns the spot price from the newspaper or by telephoning the utility.

A sophisticated interface for use in an advanced Homeostatic environment might contain functions such as:

- Conduct two-way electronic communication between the Marketplace Controller computer and the customer's computer. Spot prices are sent to the customer every five minutes. Utility customer two-way negotiations on microshedding contracts are conducted hourly. Microshedding signals when Marketplace Controller has to exercise options arrive in 2 seconds.
- Measure and record real and reactive energy flows every five minutes.
- Monitor customer response to microshedding signals to see if the contract is being honored. If not, impose a punitive rate or completely cut off supply.
- Measure frequency at the customer's location and compute the economic benefits the customer is to receive because of adjusting usage or generation in response to frequency deviations (dynamics pricing).

Such an interface might also monitor harmonic generation and provide customers with load frequency control signals for direct response. Such interfaces can be put together today using currently available equipment but commercial packages would require development efforts.

IV.4 Customer Site Communication and Decision Making

For a simple initial Homeostatic implementation involving just 24 Hour Updated Spot Pricing, an effective consumer-site system can depend on the customer's own legs and mouth for communication and head for control. However, with more advanced concepts such as 5 Minute Update Spot Price, some sort of electronic communication and possible decision making aids become necessary.

Many large customers already have in place energy management and control systems which are used to reduce peak load and to reschedule under time-of-day pricing. For such customers, Homeostatic Control is little more than a redefinition of the rules under which the energy management game is played. However, energy management equipment, as it is now constituted, is expensive to install. Hence, it is limited to fairly large customers and important energy using processes. Extension of advanced Homeostatic Control to smaller customers will require cost reductions of a substantial magnitude. Fortunately, the type of systems required are not only possible, but will and are being built, if not for use on Homeostatic Control, then for other purposes.

Consider first the question of customer site communication. If electronic communication is to be applicable to small customers and small processes, the equipment itself must not be expensive and must be relatively easy to use. Most small customers will not be sophisticated. These requirements dictate the need for a local area data network within the customer's domain which facilitates installation of various pieces of equipment in a "plug-in" fashion. There must be standardization of hardware as well as software so that pieces of equipment can be mass-produced and installed easily.

In a real sense, the local area data network within the customer's domain serves as an information analog to the local area power network (that is, house wiring) found in all buildings. The ease with which electrical appliances and devices can be installed, and indeed the relative economy of such devices, relies on the existence of such a local power network and the standard of voltage and current to which it adheres. The same thing should be true for information.

A local area data network adapted to control and monitoring applications will, in fact, be useful for tasks other than controlling electricity using devices in response to Homeostatic Control. This network will exhibit a kind of synergism. The costs associated with the network itself will be borne by more than one application system. Such a network could control lighting, intrusion and fire alarm systems, paging, entertainment systems, etc.

This local area data network has special communications needs. The messages are generally quite short, although they may be quite frequent. Often short dialogues are required; for example a space conditioning controller may inquire about temperature in a given room and expect an answer. This implies the need for some form of master/slave linking. On the other hand, if there is to be the capability of handling more than one system, there should not be a single fixed bus controller. Rather, each of the several network ports should have the capability of being bus "master" for a period of time, and then letting another port take over. With multiple, independent systems using the communications link, there is a need for a means of arbitration to determine which port can take control of the link at a particular time. Some of the messages will have a high urgency in time (such as a command to turn on a room light), while others will be less urgent (such as a thermostat reading). This suggests the need for a priority structure, so that urgent messages go ahead of non-urgent messages.

In response to the above needs for a local area data network adapted to use in control and monitoring applications, a group at MIT has specified such a network standard called COMONET which is described in Appendix A.

Finally let us consider the issue of customer decision-making under Homeostatic Control. As discussed earlier, this is just a redefinition of the rules of the game for large customers who already have sophisticated energy management and control systems. Customers without fancy electronics could react to 24 Hour Update Spot Pricing by viewing the expected price variations under normal conditions as time-of-day rates and making special adjustments only when abnormal power plant outages, weather, or fuel shortages cause very high rates. With microelectronics and advanced Homeostatic Control concepts, the actual decision making can become a sophisticated blend of electronics and humans. Residential customers without computer background might buy computer systems designed initially to allow them to learn and view their energy management much as an electronic war game. Increased sophistication could come with practice and experience. Some customers with computer background would do some of their own programming. In either case, the computers would provide the vehicle for implementing the customer's desires when living in a Homeostatic environment.

With special purpose computers as well as with communication, standardization of software and hardware interfacing, a "plug in" capability as in COMONET is essential. The tremendous increases in the performance to cost ratio of computational systems in recent years promise to put sophisticated hardware within the reach of even the smallest customers within a few years. Standardized, reproducible software can be expected to make the complete package affordable and usable.

The fanciful scenario of Figure 3 illustrates how a residential customer of the future might live out one day under Homeostatic Control.

V. Implications of Implementation

No discussion of Homeostatic Control would be complete without consideration of the cost-benefit implications.

V.1 Costs

Money is needed to develop, implement, and operate the Marketplace Controller, and the communication system between it and the customers. Communication costs would become quite high if all customers, including the smallest residence, were on 5-Minute Spot Pricing and were using sophisticated, frequently updated microshedding contracts. Given today's prices for electric power and for communication computation systems, the cost of employing highly sophisticated versions of Homeostatic Control would exceed the benefits for some customers. Fortunately the level of Homeostatic Control sophistication (i.e., cost) can be adapted to the benefits received. Those large industrial customers who are capable and willing to respond could receive sophisticated five-minute spot pricing and microshedding signals, while smaller customers or those who do not have the ability to respond could be on 24-hour update spot prices, time-of-use rates, or flat rates. A similar picture exists on the communication computation costs a particular customer might incur in order to respond effectively to the energy marketplace environment. Customers could choose the level of sophistication that matches their particular needs ranging from simple flashing light warning systems to sophisticated real-time microelectronics. One of the major strengths of the overall Homeostatic Control framework is this ability to match the cost incurred to the benefits received.

Figure 3

A RESIDENTIAL HOMEOSTATIC DAY

6:00 a.m.	o	Home owner wakes up.
	o	Computer has hot water ready for shower.
7:00 a.m.	o	Computer displays its energy use plan for next 24 hours based on predicted weather and spot price patterns, and on owner's average lifestyle which computer has learned.
	o	Owner modifies plan because guests are expected for dinner.
7:30 a.m.	o	Owner leaves for work.
10:00 a.m.	o	Computer receives revised weather forecast and then changes its space conditioning strategy for the rest of the day.
12:00 noon	o	Owner calls computer to say guests are spending the night.
	o	Computer incorporates space conditioning the guest room into its strategy.
3:00 p.m.	o	Major storm front knocks out many power plants and transmission lines
	o	Utility's Marketplace Controller exercises microshedding options, owner's computer responds by turning off space conditioning.
3:05 p.m.	o	A large quality of supply component is added to the spot price.
	o	Computer reacts to very high spot prices by turning off everything except the refrigerater, freezer and itself.
	o	Computer calls owner to tell of its emergency actions.
	o	Owner tells computer to space condition the living room in spite of the very high prices starting at 6:00 p.m.
7:00 p.m.	o	Owner starts pleasant evening in living room with guests. All enjoy lobster salad, fresh tomatoes vinaigrette and chilled white wine...

Figure 3

A RESIDENTIAL HOMEOSTATIC DAY (continued)

8:00 p.m.	o Power system restoration proceeds rapidly
	o Spot price starts to fall and is predicted to be minimum at 3:00 a.m.
	o Owner tells computer to have guest room and master bedroom space conditioned by midnight.
12 midnght	o Owner and guests retire
3 a.m.	o Computer starts to run dishwasher and laundry machines; heats water for next morning
	o Latest spot price and weather forecasts cause computer to pre-cool parts of the house so it can "coast" during the next afternoon.
4 a.m.	o Second storm front causes major power system disturbances which result in system frequency swings.
	o Computer cycles electrical usage in phase with frequency (usage down when frequency down).
	o Owner and guests keep sleeping comfortably.

The costs to be associated with implementing Homeostatic Control will be greatly reduced if many present trends in related areas continue. Utilities are presently considering sophisticated distribution and automation control systems to provide real-time control of various elements of a distribution system. Homeostatic Control could be implemented using such communication capabilities as a basis with a subsequent major reduction in the cost associated with Homeostatic Control. Industrial and commercial customers are already installing a variety of microprocessor-based monitoring and control systems on their premises. The home computer has already been moved out of the toy stage. Microprocessor-based residential security monitoring systems are coming. Given the prior existence of such systems, the addition of Homeostatic Control response capability would become very much less expensive for the customers.

V.2 Benefits

Table 1 summarizes some of the major time scales and functions associated with control, operation, and planning of generation, transmission, and distribution systems. Customer actions have a similar decomposition. Homeostatic Control provides benefits in all these time frames. In the fast control time frames, system dynamics are smoothed primarily by control of energy type loads. In the longer operational time frames, the existence of the energy marketplace increases operating efficiencies. At investment decision time scales, the impacts of uncertainties in future fuel costs, technology availability, and demand are reduced because both the customers and the generation, transmission and distributions systems are responding to changing conditions in a

Functions	Time Frame
Control of System Dynamics	
Transient stability	0 to 1 second
Dynamic stability	0.1 to 10 seconds
Long-term dynamics	1 second to 30 minutes
System Operation	
Economic dispatch	Every 5 minutes
Unit commitment	Hourly for week
Maintainance scheduling	Weekly for year
Investment Planning	
Distribution	1 to 5 years
Transmission	5 to 20 years
Generation	5 to 40 years

Table 1

TIME FRAMES ASSOCIATED WITH MAJOR FUNCTIONS cooperative fashion. The overall result is a more robust electric power system.

A wide variety of control devices are presently used to control system dynamics. Homeostatic Control would provide additional powerful new control means to the power system control engineer: namely, the ability for free, short-term control of energy type loads through customer response to dynamics pricing and via utility-exercised, short-term contract options such as microshedding. This could lead to a major evolution in control philisophy for both normal and emergency state control. Most fast-acting control might be taken off of large power plants and placed on the faster, more responsive usage devices. Thus the large expensive power plants could be operated in a smoother fashion to do what they do best; generate electric energy efficiently.

To most economists the concept of economically efficient operation of a supply-demand system holds a particular significance in that it defines the conditions under which the greatest amount of goods and services are produced for the least cost. The energy marketplace would provide a way to get very close to economic efficiency in system operation. Consider first customer operational decisions relative to usage. A spot price enables a customer to decide whether the marginal value of electric energy is sufficiently great to warrant purchasing electricity at that time. However, we do not envision a world where the cost of electricity dominates industrial customers' production decisions or residential customers' lifestyles. Most customers would not worry about their electric power consumption except at the times when they provide priorities to their computer systems (if any) and at those abnormal times when very high prices exist or are expected. However, this relatively minor involvement would improve the efficiency of operation. By adapting to price changes in a routine fashion, the customers would reduce their overall energy bill without significant changes in industrial production, residential lifestyles, etc. During times of system stress when prices are very high, individual customers who happen to have particularly important operations under way (such as a batch industrial process or a wedding) can still decide to use the energy.

Relative to the operation of the generation system, the energy marketplace would automatically cause efficient dispatch of customer-owned cogeneration or other generating facilities. Spot pricing combined with some types of microshedding would greatly reduce if not eliminate the costs of carrying spinning reserves on the major generating units. However, the biggest improvements in the efficiency of operation of the generation system occur because of the pricing feedback between the usage and generation. Fuel would be burned at times and in amounts which truly best match the customer's actual needs.

Implementation of Homeostatic Control concepts would have major implications on the types of investment decisions being made by both the customer and the utility. Some customers would make capital investments for usage devices to take advantage of changing spot prices, such as buying storage heating equipment, extra process storage, and more insulation. Such devices would help customers take advantage of low prices and avoid high prices and, with a little more sophisticated decision making, would enable customers to take advantage of microshedding contracts.

Homeostatic Control would have an impact on the types of generation plants being built. Efficient base load units would become more desirable while peaking units would lose attractiveness. Solar and wind generation would become more attractive. Homeostatic Control would apply pressure to strengthen the transmission/distribution system as the effectiveness of the energy marketplace increases with the capabilities of the transmission/distribution systems.

Homeostatic Control concepts would also change some of the basic ways in which investment planning decisions are made. For example, in generation expansion planning the concept of a reliability constraint on the allowable loss of load probability would become obsolete as generation investment decisions would now turn on the price customers are willing to pay. Questions of reliability of customer service would become concentrated at the distribution level which is where such discussions belong in the first place. The overall result would be a more robust system which is less demanding from a planning point of view because both the generation system and the customers would be responding together to the unexpected changes in fuel costs, technology, etc. which are bound to occur in the future.

If some sort of deregulation of electric generation takes place in the future and if such deregulation is done along the lines of an energy marketplace, new capital markets for generation expansion would open up. A completely free-floating spot price would enable venture capitalists to make large profits if they were able to predict the market and provide the right technology at the right time to meet a real need.

The energy marketplace and spot pricing would provide a more favorable climate for renewable generation technologies such as solar, wind, and hydro. In an energy marketplace, the capacity credit concept which can reduce the attractiveness of renewable generation is no longer viable. In an energy marketplace a kilowatt hour is worth just as much from a coal or nuclear power plant as from a solar or wind power plant. The impact of the stochastic nature of wind and solar generation on system spinning reserve requirements would be greatly reduced if not eliminated under Homeostatic Control.

The existence of an open energy marketplace would encourage innovative new technologies on both usage and generation sides. There would, of course, be a major surge in innovative methods and technologies for customer site energy management systems. As another example, consider an integrated residential system consisting of heat pump, solar array, electric resistance back-up and gas-fired (natural or coal-gasified) cogeneration. The attractiveness of such a system would be increased greatly if it could play the energy marketplace and buy when the price is cheap and sell when the price is high. In a similar fashion consider an industrial complex wherein a basic heat source (coal or nuclear) is integrated into a system which can generate various quanities of steam, chemicals, industrial gases and electricity, depending on energy marketplace conditions.

Homeostatic Control has social benefits that go beyond economic and engineering efficiency. The customers would become sensitive to the actual costs and problems faced by the utilities. Such understanding would provide a better rapport between the two. Today's regulatory process has yielded a complex set of ad hoc special rates for special cases which are confusing to customers and which cause distrust of both the utility and the regulatory commission. Optimum spot pricing provides a solid, self-consistent basis for establishing rates that are fair to all concerned. The simplifications in the basic rate-making process resulting from Homeostatic Control would prove to be one of its major benefits.

VI. Revolution or Evolution?

We believe that Homeostatic Control represents a structured evolution of the electric power system. It is a blending together of many individual directions which are currently under way within the industry. It builds upon a decade of revolution in communication and computation and nearly a decade of continued development in customer load management. To us, it is a natural and beneficial way of directing changes which are certain to occur in the future. We expect implementation of Homeostatic Control to evolve gradually. Large industrial customers are likely to be the first to find marketplace participation to be to their economic advantage. They will be followed by other customers with special types of large energy use and eventually by many residential customers. The economic benefits will be continuously netted against the cost of control and metering equipment. Throughout this whole evolution, the benefits of greater efficiency will be shared by all customers and the utilities will become better able to deal with the massive uncertainties they face.

Of course, historically, most revolutionary ideas turned out to be just an evolution of old ideas to meet a new set of conditions and needs. The ideas were considered revolutionary because their implementation had a large impact. Homeostatic Control was not needed in the past because the cost of communication and computation was high and the price of electric energy was low. Now there are new conditions and needs; the costs of communication and computation are still falling while the price of electric energy is high and rising. Implementation of Homeostatic Control can have major impacts on costs and how we as a society treat electric energy. In this sense, Homeostatic Control is revolutionary as well as evolutionary.

References*

The following is an annotated list of MIT reports and papers on Homeostatic Control:

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

2. "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.

3. "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.

4. "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. Modeling loads as random processes. Does not explicitly model effect of changes in electric rates, but suggests how to estimate these effects.

5. "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 three main elements: spot pricing, microshedding, and decentralized dynamic control. A few equations, but no formal derivations.

6. "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 possibility of spot pricing. No equations. Reference 9 develops the same concepts rigorously.

7. "Homeostatic Control: A Research Plan" by the Homeostatic Control Working Grup, unpublished, July 1980, 100 pages. An integrated research plan. Now somewhat obsolete.

8. "A Theoretical Analysis of Customer Response to Rapidly Changing Electricity Prices", by R. Bohn, 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. Executive summary.

9. "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. Executive summary. Will be updated as Technical Report MIT-EL 81-026.

10. "Deregulating the Electric Utility Industry: Discussion and a Proposed Approach", by B. Golub, R. Tabors, R. Bohn, F. Schweppe, July 1981, EL 81-043 WP, 43 pages. Discusses the requirements for a successful deregulated electric utility system. Suggests that spot pricing is the best approach to deregulating generation, but may not be enough.

11. "MIT Research Capabilities in Homeostatic Control" 11 pages, undated.

12. "Homeostatic Control: Economic Integration of Solar Technologies into Electric Power Operations and Planning," by R. Tabors. 22 pages, undated. Shows how homeostastic control can be used to overcome the problems perceived for integrating non-dispatchable technologies into a utility system. Self-contained non-quantitative discussion.

13. "Optimal Spot Pricing: Part I: In Practice," and "Part II: In Theory," by M. Caramanis, R. Bohn and F. Schweppe (9 and 7 pages). Two papers based on on #9 above written for engineering audience.

14. "Investment Planning Under Optimal Spot Pricing of Electricity," by M. Caramanis, September 1981, MIT-EL 81-051WP (30 pages). More details and extension of #9 above in investment areas.

15. "Impact of New Eletronic Technologies on the Customer End of Distribution Automation and Control," by J. Kirtley, and T. Sterling, IEEE Summer Power Meeting, July 1979, paper A79 495-3 (5 pages). A companion to #5 above with emphasis on microelectronics.

16. "Control and Monitoring Systems Communication for Effective Energy Use," by T. Sterling, R. Williams and J. Kirtley. IEEE Summer Power Meeting, July 1981, paper 81 SM 307-8 (6 pages). Discusses issues of standardization and layers of commonality.

17. "COMONET: An Intra-Building Data Link," MIT EPSPEL Memo, undated, 26 pages. Describes architecture and portrait of COMONET.

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*A complete bibliography on other related work was not attempted here. However, one pioneering work which we do want to mention is:

"Responsive Pricing of Public Utility Services," by W. Vickery, Bell Journal of Economics and Management Science, Vol. 2, No. 1, 1971.

18. "A Microprocessor Based Energy Usage Rescheduler for Electronic Utility Load Leveling," by J. Wilber, MIT EECS Bachelors Thesis, June 1981, (52 pages). Discusses microprocessing control of water heaters in presence of spot pricing.

Appendix A: COMONET

COMONET is a fully distributed communications network with all arbitration and control functionality provided by the separate interface ports. These ports interact through two signal paths, the data path and the control path. (which could be separate wires, two frequency multiplexed paths, etc.) The data path transfers all systems level bit strings and all link level command words. The control path supports the distributed arbitration structure. No central link controller is required to perform arbitration or routine housekeeping.

A bus port requests link access by sending an access request word (which designates the urgency of the request) over the control path. Each system port keeps track of the number of pending requests in each urgency class by counting access requests and signals indicating that a port relinquishes link control.

Once a link port reaches the top of its request queue, it becomes link master, and controls operation of the link by issuing command words over the data path. These control words are:

SID	Slave Identification
MSD	Master Send Data
SSD	Slave Send Data

These command words operate to change the state of the link. For example, if the master issues the command word SID, each of the other ports examines the next bit string to see if that bit string matches its address. If MSD is issued, the port previously identified as a "slave" port interprets the next bit string as data and passes it on to the attached system component. If SSD is issued, the port previously identified as a "slave" port is expected to send data. The link master relinquishes control of the network by issuing a special control word EOF, for End of Function.

It is possible to include a collision-detection, delayed re-transmission scheme in this link protocol to ensure robustness. In addition, the bus is provided with a timeout mechanism to make up for missing messages.