Back to the future:
*Spot Pricing of Electricity*  
(Schwepppe, 1988)
In 1988, MIT Professor Fred Schweppe, BU Professor Michael Caramanis, UCSD Professor Roger Bohn, and MIT researcher Richard Tabors published a book titled “Spot Pricing of Electricity” that forever transformed electricity markets in many parts of the world. Unfortunately, that same year Fred Schweppe tragically passed away.

Although Schweppe has been credited with developing the foundational concepts for competitive electricity markets, the premise of his work—demand participation—has been largely absent from most market designs. The following is a summary of the book, which has become scarcely available outside of select academic libraries. Schweppe’s original work contains detailed mathematical derivations and additional content beyond what is covered here.

The spot price based energy marketplace

Electric energy must be treated as a commodity which can be bought, sold, and traded, taking into account its **time- and space-varying values and costs**. The hourly spot price is the basis of the energy marketplace because it provides the foundation for all transactions.

An hourly spot price (in dollars per kilowatt hour) **reflects the operating and capital costs** of generating, transmitting and distributing electric energy. It varies each hour and from place to place.

The spot price based energy marketplace **involves a variety of utility-customer transactions** (ranging from hourly varying prices to long-term, multiple-year contracts), all of which are based in a consistent manner on hourly spot prices. These transactions may include customers selling to, as well as buying from, the utility. The number of different types of transactions that can occur between a utility and its customers is limited primarily by one’s imagination.

Benefits include:

- Improvements in operating efficiency
- Reductions in needed capital investments
- Customer options on the type (reliability) of electricity to be bought
A spot priced based energy marketplace is a win-win situation for both the regulated utility and its customers. The customer’s lifestyles improve because the customers are receiving more service from the use of electric energy per dollar spent. The utility has a more controllable, less uncertain world in which to operate.

There are **six basic criteria** for a good electricity market design:

- **Economic efficiency**: Motivate customers to adjust their own electric energy usage patterns to match utility marginal costs
- **Equity**: Reduce customer cross-subsidies (i.e. a customer’s charges are based on the utility’s costs to serve that customer)
- **Freedom of choice**: Provide customers with options on the cost and reliability of supply and how they choose to use electric energy
- **Customer acceptance and understanding**: Customers should be able to understand the nature of the transactions and be convinced that they are fair
- **Utility control, operation and planning**: Consider the engineering requirements for controlling, operating and planning an electric power system
- **Customer control, operation, and planning**: The customers’ reaction to transactions should not have to be unwieldy or unnecessarily complex

**Failures inherent to the current utility-customer model**

The failure of most present-day utility-customer transactions to meet today’s needs can be traced to their historical foundations. They were established by individuals unconcerned with power system control and operation, during times when communication and computation were very expensive, when there was less incentive to use electricity in an efficient fashion, and when cross-subsidies were of limited concern to society.

The six basic criteria can be achieved only by returning to the first principles of economics and engineering and by viewing the utility and its customers as a single integrated system.
Energy marketplace transactions

The best way to achieve economic efficiency, equity, and customer freedom of choice is the use of marketplace where market clearing prices are determined by supply and demand.

The five essential ingredients for a successful marketplace are

1. A supply side with varying supply costs that increase with demand
2. A demand side with varying demand levels which can adapt to price changes
3. A market mechanism for buying and selling
4. No monopsonistic behavior on the demand side (monopsony is difficult on the demand side because the number of customers ranges from thousands to millions)
5. No monopolistic behavior on the supply side

The energy marketplace is designed explicitly to include engineering issues associated with power system control and operation. The hourly spot price is determined by the demand at that hour and the hourly varying costs and capabilities of the generation, transmission and distribution systems. The hourly spot price is also defined in terms of marginal costs subject to revenue reconciliation.

The whole electric power system (generation, transmission, distribution, and customers) is controlled and operated in an integrated fashion, without removing the customers’ freedom of choice. This is made possible by the diversity in customers’ characteristics, desires and needs.

In a spot price based energy marketplace, the utility and its customers are partners working together to achieve the maximum benefit from electric energy usage at minimum cost, also considering transaction costs (e.g. cost of metering). The amount of such partnering found in present-day utility-customer relationships is small at best. Conversely, the microelectronic revolution is driving transaction costs down at a rapid rate.

The spot price based energy marketplace is the logical evolution of present-day rates and load management techniques, married with present-day practices of power system operation, the concept of utility-customer partnering, and the availability of inexpensive communications and computation equipment.
Transitioning to a spot price based energy marketplace

A spot price based energy marketplace that meets the six basic criteria can be achieved in three steps:

1. Define hourly spot prices and evaluate their behavior
2. Specify an appropriate set of utility-customer transactions based on the hourly spot price and associated transactions costs
3. Implement the energy marketplace considering the needs and capabilities of both the utility and the customers
Step 1: Define hourly spot prices

The hourly spot price is determined by the supply/demand conditions that exist at that hour. In particular, it depends on that hour’s:

- Demand (in total and by location)
- Generation availability and costs (including purchases from other utilities)
- Transmission/distribution network availability and losses

Determining the hourly spot price is a random process. Its future value cannot be predicted perfectly due to uncontrollable equipment outages and demand variations. For example, because generation outages can significantly impair supply, the highest spot prices usually will not occur at the hour of the highest demand.

Mathematical definition of hourly spot pricing

The spot price $p_k(t)$ is the marginal (or incremental) cost of providing electric energy to customer $k$ during hour $t$ taking into consideration both operating and capital costs ($$/kWh$).

Define price:

<table>
<thead>
<tr>
<th>$p_k(t)$</th>
<th>Hourly spot price for $k$th customer during hour $t$ ($$/kWh$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$d_k(t)$</td>
<td>Demand of $k$th customer during hour $t$ (kWh)</td>
</tr>
<tr>
<td>$d(t)$</td>
<td>Total demand of all customers during hour $t$ (kWh)</td>
</tr>
</tbody>
</table>

\[ d(t) = \sum_k d_k(t) \quad \text{Total demand is the sum of each customer $k$'s demand for hour $t$} \]

The hourly spot price (without revenue reconciliation) is given by the marginal cost:

\[ p_k(t) = \frac{\partial}{\partial d_k(t)} \times \text{[Total cost of providing energy to all customers now and through the future]} \]
Subject to constraints such as:

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Energy Balance</strong></td>
<td>Total generation equals total demand plus losses</td>
</tr>
<tr>
<td><strong>Generation Limits</strong></td>
<td>Total demand during hour ( t ) cannot exceed the capacity of all the power plants available at hour ( t )</td>
</tr>
<tr>
<td><strong>Kirchoff’s Laws</strong></td>
<td>Energy flows and losses on a network are specified by physical laws</td>
</tr>
<tr>
<td><strong>Line Flow Limits</strong></td>
<td>Energy flows over a particular line cannot exceed specified limits without causing system operating problems</td>
</tr>
</tbody>
</table>

**Components of hourly spot prices**

The hourly spot price associated with the \( k \)th customer during hour \( t \) is viewed as the sum of individual components defined by:

\[
p_k(t) = \gamma(t) + \gamma_M(t) + \gamma_QS(t) + \gamma_R(t) + \eta_{LU}(t) + \eta_{QS}(t) + \eta_{R}(t)
\]

[Generation marginal fuel]
[Generator marginal maintenance]
[Generation quality of supply]
[Generation revenue reconciliation]
[Network marginal losses]
[Network quality of supply]
[Network revenue reconciliation]

Building upon these components, we can define a few additional parameters:

\[
\lambda(t) = \gamma(t) + \gamma_M(t)
\]
[System lambda]

\[
\gamma(t) = \lambda(t) + \gamma_QS(t)
\]
[Marginal value of generation]

\[
\eta_{LU}(t) = \eta_{LU}(t) + \eta_{QS}(t)
\]
[Marginal value of network operation]

Finally, we define the hourly spot price in a single equation:

\[
p_k(t) = \lambda(t) + \gamma_QS(t) + \eta_{LU}(t) + \eta_{QS}(t) + \gamma_R(t) + \eta_{R}(t)
\]
The various components of hourly spot prices are not necessarily independent of each other. For example, the loss component $\eta_{L,k}(t)$ depends on the system lambda, $\lambda(t)$. The network components of the hourly spot price depend on the customer index $k$ because different customers are located at different parts of the network. This spatial pricing results from the differences in line losses and the fact that individual lines can become overloaded in one part of the network while over the remaining lines flows are sustainable.

The **system lambda**, $\lambda(t)$ component of the hourly spot price is the derivative of generation total fuel and maintenance costs with respect to demand this hour. In general, $\lambda(t)$ tends to increase with increasing total demand $d(t)$. The $\lambda(t)$ component varies over time since it depends on forced (and scheduled) power plant outages, water availability, purchase-sale opportunities, load-following costs as affected by ramp and must-run constraints, etc. When these inter-temporal constraints are important, $\lambda(t)$ may be heavily influenced by planned future events.

Ideally, lambda would be obtained as one of the direct outputs of a unit commitment logic which automatically takes care of all multiple time period dependence associated with unit startup and shutdown costs, hydro storage and dispatch, purchases and sales with other utilities, etc. An adequate approximation is usually readily calculable.

The **network loss component**, $\eta_{L,k}(t)$ arises from the energy losses resulting from transmission and distribution:

$$
\eta_{L,k}(t) = \left[ \lambda(t) + \gamma_{QS}(t) \right] \frac{\partial L(t)}{\partial d_k(t)} = \left[ \lambda(t) + \gamma_{QS}(t) \right] \sum_i 2R_i z_i(t) \frac{\partial z_i(t)}{\partial d_k(t)}
$$

- $d_k(t)$: Demand of $k$th customer during hour $t$ (kWh)
- $L(t)$: Total losses during hour $t$ (kWh)
  \[= \sum_i L_i[z_i(t)]\]
- $z_i(t)$: Energy flowing over line $i$ during hour $t$ (kWh)
- $L_i[z_i(t)]$: Losses in line $i$
  \[= R_i z_i^2(t)\]
- $R_i$: Constant depending on resistance of line $i$
Based on Kirchoff’s laws, the effect of \( d_k(t) \) on total losses and/or individual line losses depends on the physical location of the \( k \)th customer in the network. The marginal network loss component can be quite important at times of high demand even if annual percentage losses are relatively small.

The **quality of supply components**, \( \gamma_{qs}(t) \) and \( \eta_{qs,k}(t) \) are determined by market clearing forces, i.e., they simply increase when generation or network capacity limits are being approached, thus serving as curtailment premiums or reliability surcharges. Their behaviors are characterized by very small or zero levels most of the time and a large, rapid increase when the system is constrained. During such critical times, these quality of supply components dominate the hourly spot price.

**Generation quality of supply**, \( \gamma_{qs}(t) \) can be defined as a function of operating reserve margin, where this function is zero unless the operating reserve margin is below a certain level after which the generation quality of supply component rises smoothly.

\[
\begin{align*}
\text{g}(t) & : \text{Total generation during hour } t (\text{KWh}) \\
\text{g}(t) & = \text{total demand} + \text{total losses} \\
& = d(t) + L(t) \\
\text{g}_{\text{crit},y}(t) & : \text{A critical generation level based on available generation capacity and operating reserve requirements}
\end{align*}
\]

The utility tries to operate to maintain the constraint:

\[
g(t) \leq g_{\text{crit},y}(t)
\]

Schweppe’s three methods for quantifying \( \gamma_{qs}(t) \) are:

<table>
<thead>
<tr>
<th>Method</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Market clearing price</td>
<td>Set ( Y_{qs}(t) ) to be the value that causes customers to reduce usage until ( g(t) = g_{\text{crit},y}(t) ). This value depends on the amount of load reduction required</td>
</tr>
<tr>
<td>Value of unserved energy</td>
<td>Set ( Y_{qs}(t) ) such that the resulting spot prices equal the cost to the customer of unserved energy, averaged over customer end uses</td>
</tr>
<tr>
<td>Allocation of peaking plant capital</td>
<td>Base ( Y_{qs}(t) ) on the annualized capital cost of a new peaking plant</td>
</tr>
</tbody>
</table>
For example, this approach is proposed for the *peaking plant allocation method*:

\[
\gamma_{QS}(t) = A_{QS,Y} \frac{LOLP_{\gamma}(t)}{LOLH_{\gamma}}
\]

- Operating reserve margin is equal to [annualized peaking cost] × [probabilistic share of annual peak load in this hour]
- \(A_{QS,Y}\) Annualized capital cost of peaking plant (\$/kW)
- \(LOLP_{\gamma}(t)\) Loss of load probability due to generation at hour \(t\)
- \(LOLH_{\gamma} = \sum_{t=1}^{\text{12 months}} LOLP_{\gamma}(t)\) Annual loss of load hours equals the sum of lost load for each hour of the year

Alternatively, \(\gamma_{QS}(t)\) can be defined using the *value of unserved energy*:

\[
\gamma_{QS}(t) = \theta_{QS,Y}(t) \cdot \text{LOLP}_{Y}(t)
\]

- \(\theta_{QS,Y}(t)\) Cost of unserved energy (\$/kWh)
- \(\text{LOLP}_{Y}(t)\) Loss of load probability due to generation at hour \(t\)

*Note: the modeling of the cost of unserved energy is a nontrivial exercise.*

The loss of load probability \(\text{LOLP}_{\gamma}(t)\) is evaluated for hour \(t\) at the beginning of hour \(t\). If it is assumed that all events can be predicted perfectly one hour in advance, then:

\[
\text{LOLP}_{\gamma}(t) = \begin{cases} 
  g(t) > g_{\text{crit},\gamma}(t) \\
  0 \text{ otherwise} 
\end{cases}
\]

A more reasonable model has \(\text{LOLP}_{\gamma}(t)\) varying smoothly between 0 and 1 as \(g(t)\) approaches \(g_{\text{crit},\gamma}(t)\). The market clearing price approach is recommended for an ideal world. However, the other two approaches can be easier to implement in the real world. The value of unserved energy is related to but not necessarily equal to the market clearing price.
By analogy with $\gamma_{QS}(t)$, network quality of supply, $\eta_{QS,k}(t)$ becomes larger in magnitude when the capacity of the network to transport energy is being approached. Assume one particular line, say line $i$, with flow $z_i(t)$ is overloading. One structural form for $\eta_{QS,k}(t)$ is

$$\eta_{QS,k}(t) = \theta_{QS,i}(t) \frac{\partial z_i(t)}{\partial d_k(t)}$$

<table>
<thead>
<tr>
<th>$d_k(t)$</th>
<th>Demand of $k$th customer during hour $t$ (kWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$z_i(t)$</td>
<td>Energy flowing over line $i$ during hour $t$ (kWh)</td>
</tr>
<tr>
<td>$\theta_{QS,i}(t)$</td>
<td>Cost of unserved energy ($$/kWh)</td>
</tr>
</tbody>
</table>

where two ways to model the marginal cost $\theta_{QS,i}(t)$ are

- Market clearing: $\theta_{QS,i}(t)$ is adjusted until customers and generators respond to change the usage and generation patterns so that the line overload goes away.
- The derivative of a cost function with respect to $z_i(t)$ where the cost function is zero until $z_i(t)$ approaches the line overload level.

Spot prices are affected at locations throughout the network even if only one line (line $i$) is being overloaded.

In addition to real energy, reactive energy flows can also be important since they affect both real line losses and voltage magnitudes. In practice, it is sometimes desirable to include a spot price on reactive energy as well as a constraint on the allowable voltage magnitudes at each bus.

The preceding equation can be generalized by viewing the energy and prices as complex numbers whose real and imaginary parts correspond to real and reactive energy respectively. When this is done, a nonlinear AC load flow has to be used to solve the network equations instead of the linear DC load flow approximation assumed here.

Lastly, the revenue reconciliation component is a set of pre-determined values that adjust the spot price. Electric utilities are usually run by a government agency or by private industry that is regulated by a government agency. Hence there is usually a need for revenue reconciliation to ensure that energy providers do not make or lose too much money.
Approaches to revenue reconciliation include

- Use of surcharge or refund
- Use of revolving funds
- Modifying the spot price

One way to modify the spot price is through a revenue reconciliation multiplier $m$ which is applied to the generation and network spot price components, $\gamma_{os}(t)$ and $\eta_{os,k}(t)$, respectively. This structure is a special case of the Ramsey pricing method. The reconciliation multiplier $m$ is a constant which is adjusted until the expected annual revenues equal the annual target revenue. If demand response is considered, $d_i(t)$ is a function of $\rho_i(t)$ which is a function of $m$, so an iterative solution for $m$ is required.

It should be noted that revenue reconciliation undermines the symmetry in the hourly spot price when the customer is buying from or selling to the utility. This type of anomaly occurs in any pricing system, although spot pricing sometimes makes them more visible by removing hidden cross-subsidies.

Use of approximations

Computation of the true value of $p(t)$ at hour $t$ is not an easy task for several reasons. There will probably be disagreement on how some of the components such as quality of supply and revenue reconciliation should be defined, and even on the definition of system lambda (e.g., marginal versus incremental). For many implementations, approximations for losses and for the effects of multiple-period time coupling (e.g., $\gamma(t)$ depends on conditions at other hours) will be required.

The fact that the true $p_k(t)$ may not be calculated does not destroy the value of implementing a spot price based energy marketplace. The actual value calculated will be much closer to the true values than the present-day flat or time-of-use rates, etc. The goal of implementing the spot price based energy marketplace is to improve the coupling between the utility and its customers, not to achieve theoretical optimality.
Step 2: Specify utility-customer transactions

Schweppe defines three general types of transactions:

- **Price-only**: customer can use all the electrical energy desired at a quoted energy price ($/kWh)
- **Price-quantity**: customer agrees to adapt usage to meet the utility’s needs under pre-specified conditions, in return for financial reward
- **Long-term contracts**: customers engage in long-term, fixed price, fixed quantity contracts with the utility, other customers, or brokers

### Examples of price-only/price-quantity with same hardware

<table>
<thead>
<tr>
<th>Cycle Length</th>
<th>Number Periods</th>
<th>Number Levels</th>
<th>Price-Only</th>
<th>Price-Quantity: Flat Rate Plus</th>
</tr>
</thead>
<tbody>
<tr>
<td>Month</td>
<td>1</td>
<td>1</td>
<td>Flat Rate</td>
<td>Limit on monthly energy use</td>
</tr>
<tr>
<td>Month</td>
<td>2</td>
<td>2</td>
<td>Peak-Offpeak Rates</td>
<td>Limit on energy usage during peak hours</td>
</tr>
<tr>
<td>Day</td>
<td>2</td>
<td>2</td>
<td>Peak-Offpeak Rates; Peak rate charged only on critical days</td>
<td>Limit on energy usage during peak hours only on critical days</td>
</tr>
<tr>
<td>Day</td>
<td>2</td>
<td>Infinite</td>
<td>Peak-Offpeak Rates; Peak Levels specified each day</td>
<td>Limit on energy usage during peak and off-peak hours varies each day</td>
</tr>
<tr>
<td>Day</td>
<td>24</td>
<td>2</td>
<td>Peak-Offpeak Rates; Rate times specified each day</td>
<td>Limit on energy usage during peak times specified each day</td>
</tr>
<tr>
<td>Day</td>
<td>24</td>
<td>Infinite</td>
<td>24-Hour Update</td>
<td>Limit on energy usage varies each hour; respecified each day</td>
</tr>
<tr>
<td>Hour</td>
<td>1</td>
<td>2</td>
<td>Peak-Offpeak Rates; Peak times respecified each hour</td>
<td>Limit on energy usage during peak hours; peak times respecified each hour</td>
</tr>
<tr>
<td>Hour</td>
<td>1</td>
<td>Infinite</td>
<td>One-Hour Updates</td>
<td>Limit on energy usage varies each hour; respecified each hour</td>
</tr>
</tbody>
</table>
Characteristics of price-only transactions

Price-only transactions have four defining characteristics:

- **Update cycle length**: The length of time a quoted price or set of prices is valid, or the interval between new price announcements
- **Advance warning**: Length of time before the start of an update cycle that the prices are quoted
- **Period definition**: The number of separate prices that are quoted within the update cycle
- **Number of price levels**: Prices may be constrained so that they can be set only at pre-specified levels

The choice of what type of price-only transactions to offer is based on a tradeoff between the transactions costs (metering, communication, computation, etc.) and the benefits obtained from the transactions.

In general, **benefits tend to increase as transactions become closer to continuous hourly spot prices**, i.e.:

- Update cycle length is reduced
- Period definition is increased
- Number of price levels is increased

The benefits of transactions also increase with the size of the customer and with the customer’s ability to respond.

To illustrate, consider a 24-hour update where prices change each hour even though they are pre-specified many hours in advance:

\[ p_k(t|\tau) \text{: Price for } k\text{th customer at hour } t \text{ defined at hour } \tau \text{ (S/kWh)} \]
For example, a 24-hour update price quoted at 4 PM for the hour between 9 and 10 AM the next day would have $\tau = 4$ PM and $t = 9$ AM.

$$ p_k(t|\tau) = E\{p_k(t)\} + \text{covariance term} $$

$E\{p_k(t)\}$: Conditional expectation of the hourly spot price $p_k(t)$ given all available information at hour $\tau$

*Note: The covariance term can generally be ignored unless a long update cycle is used.*

In other words, $E\{p_k(t)|\tau\}$ is the best guess of $p_k(t)$ given information at time $\tau$. This will be discussed further in the context of forecasts.

**Customer response to price-only transactions**

When discussing customer response, it is helpful to aggregate hourly spot price components into

- **Normal operating components**: hourly spot price components associated with normal operation when the system’s capacity is not being approached, i.e. $\lambda(t)$, $\eta_l(t)$, $\gamma_R(t)$, $\eta_R(t)$
- **Quality of supply components**: the $\gamma_{Qs}(t)$ and $\eta_{Qs}(t)$ components which are very small or zero most of the time, but dominate the normal components during times when the system’s generation or network capacity is being approached

Customers can respond to normal price variations by

- **Ignoring the variations**: customer finds that the normal variations are insufficient to justify any response
- **Treating them as pre-specified time-of-use**: customer responds to normal variations only in an expected value sense, where expectation is over months, and makes no attempt to respond to the day-to-day variations
- **Real-time response**: customer responds in real-time both to changes in the forecasts of future spot prices and their actual variations
The customers who respond in real time to normal spot price variations often view their tactical interventions as being divided into two parts:

- **Long-term** (say a day to weeks) control decisions based on forecasted spot price behavior and forecasts of other variables such as weather and production needs
- **Short-term** (say hourly) deviation from long-term schedule, to respond to unexpected changes in hourly spot price, weather, etc.

If services provided by electricity are extremely valuable to a customer at a particular time, that **customer may choose not to respond, but this is different than ignoring the spot price.** Customers usually cannot respond in a pre-specified manner to the quality of supply components because, for most situations, it is difficult to predict more than a day in advance the exact hours when these quality of supply components will be active.

The magnitude of the quality of supply components can justify **heroic response mechanisms which are not easy to preprogram into a digital computer.** Customers often plan in advance to determine how they will respond to high quality of supply components. The level of sophistication of such preplanned strategic decisions ranges from elaborate shutdown and rescheduling techniques for large industries to a residential customer who simply decides to turn down the air conditioner, tell the kids to stop watching TV, minimize cooking, and to turn off all nonessential lights.

**Characteristics of price-quantity transactions**

Price-quantity transactions involve a **short-term utility-customer contract** and include as special cases present-day interruptible contracts and direct load control.

In essence, price-quantity transactions can be viewed as procedures which **allow customers to choose their own reliability levels.** Customers who choose to buy interruptible energy do so by communicating the secure energy level they want, so that all usage above that level is at the interruptible price.
Use of price-quantity transactions instead of price-only transactions can be motivated by:

- A need for fast acting, accurate load control (seconds to minutes rather than hours) to maintain power system security
- A desire to reduce transactions costs below those of rapidly varying price-only transactions (some price-quantity transactions are cheaper to implement than some price-only transactions)

It should be noted that under the conditions of the energy marketplace where there are a huge number of customers with large diversity in usage patterns and needs, the use of prices is far superior to a quantity control with respect to both reducing transaction costs and increasing benefits.

In fact, Schweppe recommends major reliance on price-only transactions with price-quantity transactions playing only a support role to deal with particular needs such as operating reserves. For example, the use of a one-hour update spot price combined with an interruptible contract (a type of price-quantity transaction) enables corrections to be made for especially bad weather forecasts or plant outages.

The basic idea underlying many price-quantity transactions is for customers to pledge (or contract) an amount of demand which the utility can control under certain circumstances. In return, the customer receives a monetary incentive.

<table>
<thead>
<tr>
<th>Type of pledge:</th>
<th>Fixed amount of energy reduction over some time interval</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Fixed amount of power level reduction</td>
</tr>
<tr>
<td></td>
<td>All energy above a pre-specified level</td>
</tr>
<tr>
<td></td>
<td>Reduction of power to a pre-specified level</td>
</tr>
<tr>
<td></td>
<td>Control of a particular appliance or process</td>
</tr>
<tr>
<td>Override capability:</td>
<td>The customer has the right to buy-back the pledge, i.e. to override any utility control signals, with a subsequent penalty of some sort</td>
</tr>
<tr>
<td>Incentives:</td>
<td>A priori payment (i.e. payment for the pledge)</td>
</tr>
<tr>
<td></td>
<td>A posteri payment (i.e. payment only when control is exercised)</td>
</tr>
<tr>
<td></td>
<td>Combined a priori and a posteri payments</td>
</tr>
<tr>
<td>Utility control logic:</td>
<td>The utility may have information on the relative values of the energy for different customers which is used to determine control actions</td>
</tr>
</tbody>
</table>
Consider a situation where it costs the utility 0.5¢/kWh to maintain the necessary operating reserves. In this case, the utility could offer a 0.5¢/kWh discount on its regular energy rate to customers who are willing to **help carry the operating reserve by rapidly reducing load** when a sudden, unexpected loss of a major generator occurs.

An alternate procedure is for the utility to auction off price-quantity contracts so that customers themselves to bid for the amount of interruptible service they desire and the price they are willing to pay for it.

In addition to the above, characteristics which are analogous to price-only transactions such as update cycle length, number of levels, advance warning time, etc., apply as well.

**Customer response to price-quantity transactions**

For many types of price-quantity transactions, the utility exercises its right to limit quantity usage under a price-quantity contract only at those times when the quality of supply components of the hourly spot price dominate. Thus, when the quality of supply component is large there is a close relationship between customer response mechanisms to price-only transactions and their response to price-quantity restriction signals sent by the utility.

One aspect of price-quantity transactions which is not found in their price-only counterparts is the issue of **what happens if the customer does not fulfill the contracted quantity change** when so requested by the utility. Three possible approaches are

- Failure to comply causes dollar penalty
- Failure to comply causes loss of right to participate in future price-quantity transactions
- Failure to comply causes shutoff of all service

The dollar penalty actually converts the price-quantity contract into a price-only transaction.

In general, as the nature of the price-quantity transaction becomes more sophisticated, it becomes more **difficult to predict customer response**. A price-only transaction is inherently easier for customers to understand than most, if not all, price-quantity transactions.
Characteristics of long-term contracts

Long-term contracts are fixed price and fixed quantity contracts. They play a different type of role than price-only and price-quantity. When applied over a long-term period such as months or years, these contracts provide customers with risk hedging.

<table>
<thead>
<tr>
<th></th>
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<tbody>
<tr>
<td>1,000 kWh</td>
<td>Pays $100</td>
<td>Pays $100</td>
</tr>
<tr>
<td>2,000 kWh</td>
<td>Pays $100 + $90 = $190</td>
<td>Pays $100 + $110 = $210</td>
</tr>
<tr>
<td>0 kWh</td>
<td>Pays $100 − $90 = $10</td>
<td>Receives $110 − $100 = $10</td>
</tr>
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</table>

Customer has a contract for 1000 kWh at 10 ¢/KWh

As with the bidding for price-quantity contracts, there are many possible ways the market mechanisms can be developed. For example, long-term contracts could be offered that

- Are based on prediction of future costs
- Are sold to the highest bidder

A futures market in long-term contracts can be managed independently of the utility, and there are many advantages to such an arrangement. Possible arrangements include

- A broker system which enables customers’ investors, and other parties to establish the market value of future quantities of electric energy
- An insurance system wherein regional or national companies offer customers fixed-quantity insurance policies
- Possibly a formal market, in one of the established commodity market places

The basic approach is to offer fixed-price, fixed-quantity long-term contracts for specific future time intervals. The use of fixed-price, fixed-quantity long-term contracts could evolve into a futures market, with continual trading of future rights.

A variation on this long-term contract is the option wherein the customer buys the right to buy up to a fixed amount of energy at a fixed price. The customer exercises the option if the hourly spot price turns out to be greater than the option price.
Customer considerations in choice of transactions

The choice of energy marketplace transactions to be offered must consider customers’ desires and needs. Conceptually such needs can be incorporated by modeling customers’ responses, but in practice it is better to consider customers’ points of view in a more explicit fashion.

Issues of concern to customers include

- Maximizing the perceived benefit received from using electric energy
- Maximizing value added for electricity (for a firm)
- Minimizing the complexity of the transactions
- Minimizing the monthly bill
- Minimizing the uncertainty in bills and availability of energy
- Maintaining maximum control over their own fortunes
- Developing a feeling of partnership with their utility (i.e., the utility is not the enemy)

Impact of uncertainty on choice of transactions

If the desire to minimize uncertainty and complexity were the only criteria, customers would rarely choose to go on a faster price-only transaction. However, the potential of a reduction in the bill (or increasing the difference between the benefits received and the bill) can provide very strong motivation to choose a more sophisticated transaction.

Relative to the uncertainty issue, many customers are initially appalled when they think about the possibility of having to face very high prices (e.g. one dollar per kilowatt hour) at some times. However, after consideration, customers realize that their prime concern with uncertainty is not the hourly spot price itself but rather the uncertainty in their monthly and yearly electric energy bills. A highly fluctuating hourly spot price (due to both normal and quality of supply components) can result in monthly and yearly energy bills which are quite predictable because of time-averaging effects. In fact, customers can use their capability to respond to reduce the uncertainty in the energy bills.
Customers who appreciate the potential of the energy marketplace will welcome wide variations in normal spot price behavior, and the times when the quality of supply components become very large. Variations provide the customers the greatest opportunity to save money and reduce their monthly bills and/or increase the benefits they receive from electric energy.

It should be noted that as long as $\rho(t)$ and $d(t)$ are positively correlated (i.e., $\rho(t)$ tends to increase as $d(t)$ increases) then on average the spot price will never exceed the equivalent flat rate ($r_{flat} > \rho_{ave}$).

**Step 3: Implement the energy marketplace**

**Changing the status quo**

Implementation of the energy marketplace involves the utility and its customers operating as partners.

- Utility operators and planners are used to making decisions without detailed consideration of rates and customer reactions
- Customers may not be happy with the bills they presently pay, but often suspect that change is just another way for the utility to extract more money
- Industrial customers may have built their plants in ways that require modifications to be able to respond effectively to price changes

In order to address such concerns, an energy marketplace can be implemented by a gradual transition from the present system.

**How do we get customers to transition?**

One key issue in designing an energy marketplace is the question of how to evolve customers from the present-day system into a full energy marketplace.
There are four basic stages leading towards the eventual full energy marketplace

1. **Demonstration and test:** an experimentation and learning phase used to gather data and experience
2. **Initial implementation:** applied only to selected classes of customers
3. **Commitment to a spot price based energy marketplace:** this is a major milestone wherein the utility and regulatory commission announce to the customers a firm commitment to the establishment of a spot price based energy marketplace for all customers
4. **Full scale implementation:** this changes the utilities and their customers plan and operate their lives

After a commitment to the energy marketplace has been made, it is essential to **embark on a major educational process** so that all customers can learn the opportunities that will exist within the energy marketplace and how they can best take advantage of them. It is also necessary for the electric utility operators, planners, etc. to learn what type of impacts the energy marketplace will have on their operations and planning functions.

During the initial implementation phase, **restricted classes of customers** are offered hourly spot price based transactions. Revenue reconciliation can then be done only for these classes. However, it will be necessary, as soon as possible, to make all rates consistent by basing them on the hourly spot prices. If this is not done, there can be major discrepancies in equity between the costs borne by those customers under spot pricing and other customers.

The recommended approach is to establish a **mandatory minimum sophistication level** of price-only transactions for different customer classes (e.g. industrial customers see real-time updates while residential customers see billing period updates). Customers should have the option to choose price-only transactions with faster cycle lengths or more detailed levels and to engage in price-quantity transactions. The additional costs are either assigned to the customers in terms of fixed charges or factored into the price contracts.
It is logical to begin with large industrial or commercial users for the implementation of sophisticated energy marketplace spot price based transactions, since the classical cost-benefit tradeoffs are maximum for this class. However, residential customers who have sophisticated electronic communication for other purposes also constitute an important area for initial implementation of sophisticated spot price transactions.

Furthermore, the psychological impacts on the residential customers of having more control, comfort, or productivity in their own lives may justify their seeing sophisticated spot prices even if a strict dollar-based cost-benefit tradeoff does not. The importance of this last point must be emphasized. Narrow engineering-economic cost-benefit analysis based strictly on dollars can be very misleading relative to what is socially desirable in the long run.

Customer classes

While in theory each customer could have a different spot price, in practice most customers will just be divided into classes with the same price. In an energy marketplace, customer classes can be defined in various ways:

- The voltage level at which the customer receives service
- Geographical location, if the network capital costs and losses vary widely
- A given customer’s demand characteristics

Life-line (or base-line) rates refer to the use of low, non-cost-based prices for particular classes of low income or otherwise needy customers. Life-line rates can definitely be incorporated into an energy marketplace if so desired.

Customer classes who benefit from cross-subsidization under present-day rates will be extremely unhappy with an energy marketplace wherein they have to pay a fairer share of the costs.
Approaches to customer decision-making and control

Customer response to energy marketplace signals can be divided into two levels:

- **Strategic decision making**: determines the overall customer response policy. For example, for space conditioning control, a strategic decision is storage.

- **Tactical control**: combines real-time energy marketplace signals with other information such as temperatures, production schedules, etc. Determines the actual real-time response.

The two main tools used to perform these decision and control functions are **human beings and digital computers**. Strategic decision-making is a human responsibility, which can be aided by computer simulation and analyses. Tactical control can be done by human beings, by digital computers, or by various combinations thereof.

For end uses such as lighting, the service provided by electric energy, i.e. light, is provided at exactly the same time that electric energy is consumed. However, for other types of end uses such as space conditioning, the **electrical energy may be converted into thermal energy** (heat or cold) at one hour which is then used to provide the service to the customer (i.e., desired temperature) at some other hour.

Keeping this distinction in mind, some general categories are:

- **Reschedule service to different time**
- **Obtain service from another energy source**
- **Do without service**
- **Obtain extra service**
- **Reschedule usage**

The rescheduling of usage always involves some type of storage. Examples are:

- **Thermal storage**, inherent: preheating and cooling of the building shell or materials
- **Electrical storage**: batteries
- **Pressure and gravity**: water pumping, air compressing, gas storage
- **Product storage**: rescheduling of industrial production by storing semi-finished or finished products
- **Working hours**: shifting work hours or assigning workers to other tasks for a few hours
Characteristics of residential customers

The key issue in residential is the character of the electronic support system that is provided. If a residential customer has available a well designed microprocessor-based information and control system with user-friendly interface, extensive response can be expected.

Consider a sophisticated residential customer who sees a 24-hour update or one-hour update spot price combined with forecasts of future prices.

The residence is equipped with digital logic, internal communication, metering and control hardware, and a user-friendly human-computer interface (displays, buttons, etc.) Two-way electronic communication exists with the utility. The overall digital display and control system can be viewed as an expert system combined with optimization logics.

The customer’s use of the functions evolves as they gain experience, especially under price-only transactions where they do not have to figure out in advance how they will respond.

The following functions are performed by this system:

- Help customer understand, learn their desires, and warn them of high prices
- Provide routine control and special control
- Suggest heroic control for extreme situations
- Develop mathematical models for use in control logics and customer understanding
- Communication with utility to better forecast the impact of spot price changes on aggregate customer response

The existence of the energy marketplace can cause the residential customer to purchase new appliances, etc., that are better able to respond. As time goes by, appliance manufacturers will start to produce appliances designed to be able to exploit time-varying prices.
Characteristics of industrial customers

While industrial customers are large enough that the **transaction costs are much less of a barrier** than for residential customers, there are still some issues to consider.

The initial reaction of an industrial plant manager to the idea of facing a real-time spot price can be expected to be negative. However, in most cases this **negative reaction can be turned around**.

<table>
<thead>
<tr>
<th>POTENTIAL ISSUE</th>
<th>SOLUTION</th>
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<tbody>
<tr>
<td>Possibility of very high energy rates at certain times</td>
<td>Existence of very low energy rates at other times and the death of the demand charge</td>
</tr>
<tr>
<td>Concept of moving entire work shifts around</td>
<td>Large electricity-using devices whose operation can be rescheduled without affecting more than a few workers</td>
</tr>
<tr>
<td>Uncertainty associated with rapidly varying rates (hours to days)</td>
<td>Appreciation that a fluctuating market is a place where money can be made</td>
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</table>

In the real world other factors also play a key role. These factors include the nature of union contracts, the management of the company (locally owned or part of a big corporation), and the character of the work force (social background), the location of the plant (is it safe to work there at night).

Industrial **response is usually a very nonlinear function of price**. Doubling the price from 5 to 10 ¢/kWh may create little response, while doubling it from 10 to 20 ¢/kWh could cause sizable reaction because of the threshold effects. It is also clear from Schweppe’s research that price differentials during a day can be equally if not more important than the absolute value of the price.

Role of price forecasts for customers

Customers need a forecast of future energy marketplace conditions in order to make tactical operational changes and strategic capital decisions. These forecasts can be provided by the utility or by outside consulting firms.
For example, industrial response can be greatly increased if the customers know a few hours to a day in advance when exceptionally high or low prices will or are expected to occur. Such lead or warning time allows rescheduling of high-energy-consuming processes with much less cost.

Map of customer-utility interactions

[Diagram of customer-utility interactions]

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Map of customer-utility interactions

[Diagram of customer-utility interactions]
Capital investments for customer participation

In order to participate in the spot price based energy marketplace, customers need to decide on capital investments that will allow them to become price-responsive such as energy control systems, new process devices, storage systems, etc.

A necessary condition for customers to make capital investments is that the utility and regulatory commission make a **firm commitment to the establishment of a spot price based energy marketplace** and define the rules under which it will be operated (such as methods of quality of supply computation, revenue reconciliation, etc.). Unless such a commitment is made, customers will be very reluctant to make capital investments unless the payback period is very short (e.g., one to two years).

Examples of possible capital investments are

- **Add storage capacity**: addition of thermal, electrical or process storage enables the customer to better reschedule usage without major effects on service or overall production
- **Add fuel switching capability**: use gas or oil when the price of electricity is high, electricity at other times
- **Add cogeneration or self-generation**
- **Add process monitoring and digital diagnostics**: use sensors and computers to see where the electric energy is being consumed.
- **Add digital computers**: for use in either direct load control mode or as an expert system to aid plant and building operators

Utility-provided control equipment and services

One basic premise of the spot price based energy marketplace is that the utility does not act like Big Brother and take over customer decision-making prerogatives. However, **utility can provide control hardware and services for the customers** (particularly residential and small commercial).
Spot Pricing of Electricity (Schweppe, 1988)

For example, the utility could offer to provide digital computers, switches and internal communication systems which will respond to hourly spot prices and other inputs as a tactical control service. This does not constitute utility Big Brother action provided the customer specifies the strategic decision-making logics to be used by the hardware. The utility-provided system simply implements the customer’s desires.

A customer selling the utility the right to directly control individual appliances is usually a special type of energy marketplace price-quantity transaction or a price-only transaction in disguise. The customer would probably want to maintain the power to override realizing that each override costs money. The key question is whether or not it is a desirable type of transaction.

For example, the utility has no way of knowing how important the air conditioning is to any one customer at any one time. Thus control might be exercised at a particularly bad time (such as when the customer is holding a very important dinner party); the result is a very unhappy customer.

**Impact of spot prices on utility system operations**

A spot price based energy marketplace can yield major reductions in utility operating costs because customers see prices directly related to the actual operating costs occurring at that time. Spot prices provide closed loop feedback control which reduces the impact of uncertainty.

Spot prices are control signals which are available all the time and which can get as large as needed, as often as needed, while still reducing overall customer bills. The market coordinator keeps supply and demand in balance by continuously adjusting the spot price:

- Each generator self-dispatches itself by generating if the spot prices paid for electric energy exceeds the plant’s marginal operating costs
- Each customer makes long-term strategic decisions and short-term tactical adjustments to their electricity demand
All of the basic present-day power system operating functions are maintained in an energy marketplace, but some of the functions are modified:

- Short-term-demand forecasts now include the effects of price
- Unit commitment logics incorporate the effect of price feedback
- Operating reserve requirements are carried by the load or generation, whichever is least expensive

There are two ways in which price feedback influences system operations:

1. It makes the lives of system operators more difficult by introducing a new set of numbers (e.g. prices) which they have to handle
2. It makes the lives of system operators easier by giving them new control capabilities which reduce the impact of uncertainty and reduce (eventually eliminate) the trauma of having to resort to rotating blackouts or other unpleasant control actions

Economic security functions have to take into consideration the existence of uncertainty arising from equipment outages, errors in weather forecasts, etc. The energy marketplace will have a sizable impact on unit commitment logics, since an additional feedback-iterative calculation is required to handle the effects of price on demand and demand on unit commitment. Although the energy marketplace complicates the unit commitment computations, the feedback has the very positive advantage of reducing the impacts of future uncertainty on operating costs, and hence provides a more efficient unit commitment behavior.

Also, operating reserve margins can be reduced if customers carry some or all of the necessary operating reserve. To maintain system security, power systems always try to operate with sufficient operating reserve. The energy marketplace provides a mechanism for moving these operating reserves from the generators to the customers.
Role of price forecasts for utility system operations

An electric utility needs to predict future load behavior on time scales ranging from hours to years. Information on expected future behavior is essential for making control, operating and planning decisions.

Present-day load models incorporate only weather and time dependence. The modeling of price effects cannot ignore the impact of rescheduling of demand; in other words, the demand at hour \( t \) depends on both the price at hour \( t \) and the prices and demands at other times before and after the hour \( t \).

Utilities do not need to be able to model (predict) the response of individual customers to price. The utility is only concerned with aggregate customer response. Because of the diversity between customers, relatively simple response models can be used. As the degree of penetration of spot price based rates increases, sufficient data will have been obtained to develop such models.

The detailed information on customer usage patterns and priorities provided by marketplace transactions is a major aid to long-term planning. For example, the damping effect price feedback has on the impacts of uncertainty should make the overall planning process more accurate for an energy marketplace.

A major source of uncertainty is the long-range response of customers to the energy marketplace, e.g. the type of equipment (both control and end use) they will install to exploit the potentials of the marketplace.

Schweppe believed that long-range energy marketplace load modeling will be done almost entirely in terms of modeling the effects of price-only transactions, since their effects are much easier to handle than most price-quantity transactions.
Long-term capacity planning

The energy marketplace has a long-range impact on generation and network capacity requirements. In many situations, the result is a **reduction in installed capacity** (per unit of demand) and **less reliance on generation peaking units**.

Ideally, customer-utility transactions reduce the required investments for new generation, transmission and distribution by providing very strong incentives for customers to **reduce demand during those few critical hours** of a year when the utility system is approaching its capacity.

The size of real-time pricing signals during the few critical hours can be very large compared to time-of-use (TOU) variations because TOU rates correspond to average conditions. As a result, **customers on TOU rates usually have little incentive to reduce demand at critical times** because the swing in TOU rates is too small, and the high TOU rates are in effect for many hours a week.

Also, price-quantity arrangements such as direct load control often involves contracts with customers which limit the number of utility control actions, so the reduction in annual operating costs is greatly reduced.

Reactive power, spinning reserves, and frequency regulation

The market coordinator uses the available reactive control inherent in the network to maintain voltages within limits, as much as possible. However, when the voltage control capabilities of the network are exceeded, or when line flows threaten to exceed their thermal or dynamic limits, the participants’ generation and usage patterns are changed by introducing **network quality of supply components for reactive power** into customers’ spot price for energy.

The market coordinator maintains **sufficient reserve to respond to major unexpected generation losses**, dying tie-line support, and other dilemmas using price-quantity contracts which can be exercised as needed. Either the customer would be paid up front, or a very substantial payment would be made whenever the option is exercised. Analogous contracts with generators provide spinning reserves.
An interconnected system of generators can display oscillating or unstable behavior due to either small or large (e.g., faults) disturbances. Users and privately owned generators who aggravate such undesirable dynamic behavior are penalized (charged extra) by the T and D company while those whose characteristics improve overall dynamic behavior are rewarded (paid).

**Role of the regulatory commission**

The main responsibilities of the regulatory commission in establishing a spot price based energy marketplace are a commitment to its establishment, the specification of the price formulas, and the monitoring of the utility’s behavior.

A key regulatory commission planning decision is when to **make a firm commitment to the establishment of a spot price based energy marketplace**. This will not necessarily be an easy decision. For example, customers who are being cross-subsidized under the present system of rates will tend to complain rather loudly about changes which result in more equitable sharing of costs.

In a spot based energy marketplace, the regulatory commission has to specify (or accept) a **formula for calculating the spot prices** rather than specify a particular numerical value for a particular rate. This requires decisions on which quality of supply approach to use, how much network detail to include, etc. Fortunately there exist various precedents for such a procedure. The fuel adjustment clause is one example. Present-day interruptible rates and many direct load control schemes also provide precedents that are closer in time scales of operation to hourly spot prices.

The **detailed calculations for achieving revenue reconciliation** change under spot pricing, but the principles remain the same. The regulatory commission still has to decide each year what costs can be put into the rate base, what a reasonable rate of return on investment is, etc. Customers may be concerned that without such close monitoring, the utility would manipulate prices to increase their profits. Concern over possible price manipulation can be handled through revenue reconciliation.