Electricity Pricing: Load Management
via Consumer Storage

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Despite a vast theoretical literature on peak load pricing and intense policy interest in energy conservation, there has been very little rigorous analysis of electricity load management options. This paper presents a theoretical framework for evaluating utility and consumer investments in storage capacity to reduce electricity generation costs. Utility managers and regulators have expressed interest in storage programs, yet they tend to evaluate them in inconsistent or incorrect ways.[1]

I. Policy Initiatives

Given the size of the investments involved here, it is important that regulatory policies toward shaping customer loads reflect state-of-the-art benefit-cost analyses. In the United States, energy legislation passed in 1978 included two complementary (but potentially conflicting) approaches to perceived energy problems, reflected in the Public Utility Regulatory Policies Act (PURPA) and the National Energy and Conservation Act (NECPA). The former focused on rate design issues, as it required state regulatory commissions to determine whether a set of rate-making standards should be implemented. In response to PURPA, state regulators held numerous hearings to evaluate declining block rates, interruptible rates, time-of-day (TOD) prices, and direct load control (DLC). The various rate designs are often viewed by policy-makers as alternative techniques for load management. Changes in the daily load shape can result in reduced capacity requirements and lower fuel costs. Of course, to achieve economic efficiency, the utility's comparison of alternative load management strategies needs to account for both avoided costs and impacts on consumer surplus. Unfortunately, PURPA has not resulted in a consistent application of benefit-cost analysis for electricity rate design. However, the legacy of NECPA (the energy conservation act) is even more dismal.

Under NECPA, utilities are mandated to help customers improve the energy efficiency of their homes through a residential energy conservation service (RECS). State regulatory commissions have been evaluating approaches to conservation, including the provision of information (through energy audits) and direct investment in equipment (such as thermal storage units and insulation). The joint effects of PURPA, NECPA, and RECS might be labeled Public Authorities Nonchalantly Implementing Conservation, or PANIC.

From the standpoint of economic efficiency, regulatory policies must take an integrated approach to utility pricing and capacity investments, which incorporates customers responses directly into the analysis--in terms of short term behavioral changes and consumer investments. The more piecemeal PANIC approach tends to focus on initial cost-avoidance, ignoring further customer adjustments, which could jeopardize the cost-effectiveness of particular utility programs. In addition, the supportive role of price signals is seldom given much weight in the regulatory process. Rather, all customers tend to be charged for conservation services received by only a few.

Marino and Sicilian (1982) modeled the implications of several regulatory policies, including rate base treatment of conservation investments. They stress the importance of the cost-recovery scheme in determining utility (and customer) incentives. Here, we abstract from rate base regulation features of the problem to show key relationships between price and "conservation" policies. In the PANIC approach, a policy might appear to be "cost-effective" from the utility's standpoint, but be uneconomic from the perspective of overall resource allocation. Either under or overinvestment could occur if regulators adopt improper criteria.

The choices facing regulators and managers are very complex, with mutually exclusive investments and hybrids (involving joint costs) complicating the decision-making process (see Hakki and Chamberlin, 1981). Regulators recognize that innovations in rate design are not costless. To implement a time-of-use price structure for residential customers, companies must make significant investments in metering equipment. For many customers, the improvements is resource allocation will not outweigh the costs of a mandatory program. Similarly, direct load control, which interrupts service to particular appliances (such as air conditioners or hot water heaters), involves investments in meters and communications systems. Proposed (and operating) NECPA programs also can require large infusions of funds--diverted from construction programs or funded through higher allowed rates of return for the utility. One such program, thermal storage, will be used to illustrate the essential trade-offs involved in implementing load management through customer storage facilities.[2]

II. Previous Research

Economists have considered the storage problem from the perspectives of producer and consumer incentives. Gravelle (1976) presented a detailed analysis of the peak load problem with feasible storage, examining how the welfare-maximizing, peak/off-peak price differential depends on storage costs (say, for pumped storage). Assuming welfare-maximizing prices, generating capacity could be larger or smaller with storage, depending on two factors. First, consumption levels change, resulting in the substitution of more highly valued peak consumption for off-peak consumption; and second, production levels change, altering the system cost savings from new capacity. Gravelle notes that when the firm is constrained to charge a uniform price, regardless of demand conditions, only the cost reduction motive holds. He concludes that the pricing regime, financial targets, cost conditions, and demand conditions determine whether storage and production capacity are complements or substitutes. Although he develops a comprehensive model, Gravelle does not address investments by consumers in storage.

In more recent studies, Marino and Sicilian (1982, 1983) examine utility incentives to make direct conservation investments: they focus on the rate of return constraint and alternative regulatory strategies. Rate base treatment of such investments and customer payments for insulation and other programs have implications for effiecincy. They conclude that some current electric utility rules lead to underinvestment in conservation.

Our approach is to use a standard peak-load model with consumer storage to capture the essential features of the problem. We assume that the regulators want to improve the efficiency of power production, but they have determined that time-of-day pricing is not cost-justified. While choosing load management via consumer storage facilities as the alternative, regulators want to implement the program so that both the consumers and the utility are made better off. Thus, consumers must be provided an incentive to cooperate, and the utility must enjoy an increase in profits. Our model explores conditions that make this possible under two scenarios: 1) the utility covers the cost of storage, and 2) the consumer covers the cost of storage.

III. Storage when the Utility Covers the Cost

Following much of the peak load literature, consider a utility offering service in equal-length peak and off-peak periods, where the former is a firm peak.[3] Operating costs per kilowatt hour are given by b, while generating capacity costs are β per kilowatt. The utility is regulated and profits are constrained to some non-negative quantity, which is less than what could be earned in the absence of regulation. We ignore Averch-Johnson considerations. A uniform price, p, is charged for each kilowatt hour in both periods. For simplicity, let there be zero excess profits, so that the following holds throughout:

$$b < p < b + \beta. \tag{1}$$

Load management via storage is to be implemented as follows. the utility installs a storage system at the consumer's location. During off-peak periods, storage is filled by the utility and then is drawn down by the consumer in the following peak period. Some element of direct load control must also be present to prevent re-filling (or re-charging) of the storage unit in the peak period. Thus, peak demands are satisfied by less expensive off-peak power. The utility covers the cost of storage and provides the consumer a payment to encourage voluntary participation in the program. The payment is taken to be proportional to the size of the storage system installed. The utility's incentive to participate is that less generation capacity will be needed: The utility will find that program profitable only if the savings in generation capacity costs are sufficient to cover the storage costs and incentive payments.

Let x_o^i and x_p^i be the differentiable demand functions of consumer i for electricity in the off-peak and peak periods respectively, where i = 1, . . . , m. Storage capacity in kilowatt hours is given by s^i and its cost is $C(s^i)$, where again, i represents consumer i. $C(s^i)$ is assumed to be twice differentiable with $C'(s^i) > 0$ and $C''(s^i) > 0$. Because storage is not perfect in its ability to hold energy from the off-peak to peak periods, there is some loss in the system. We assume that the consumer does not have to pay for this loss.[4] Denote storage efficiency by e so that one kilowatt hour stored in the off-peak provides e kilowatt hours in the peak, where $0 < e < 1$.

A consumer that demands x_p^i will have L^i of this demand curtailed. If the consumer is to continue enjoying the service of x_p^i kilowatt hours, then L^i must be drawn from storage. In turn, this requires s^i kilowatt hours be placed in storage during the off-peak so that es^i is retrieved during the peak, where $es^i = L^i$. The assumption used here is that storage is designed to exactly offset the curtailed peak power, and the consumer is indifferent to receiving power directly from the utility or from storage. Alternatively, the utility does not curtail service by more than what storage can supply.[5]

Profit can be written as

$$\pi = \sum_{i=1}^{n} p(x_o^i + x_p^i) + \sum_{i=n+1}^{m} [p(x_o^i + x_p^i) - \alpha L^i \beta] - \sum_{i=1}^{n} b(x_o^i + x_p^i)$$
$$- \sum_{i=n+1}^{m} b[x_o^i + s^i + x_p^i - L^i] - \sum_{i=1}^{n} \beta x_p^i - \sum_{i=n+1}^{m} \beta(x_p^i - L^i) - \sum_{i=n+1}^{m} C(s^i) \tag{2}$$

From the m consumers, n of them do not participate in the load management program, while the remaining m-n do participate. The first term in (2) is the revenue from the nonparticipants, and the second term is the revenue from the participants. In the latter term, $\alpha L^i \beta$ represents the incentive provided the i^{th} consumer where $0 < \alpha < 1$ and $L^i \beta$ is the generation capacity savings enjoyed by the utility. The third and fourth terms are the operating costs of supplying nonparticipants and participants, respectively. For participants, an L^i is subtracted from the peak to account for the curtailment, and an $\underline{s}^i$ added to the off-peak to account for filling storage. The fifth and sixth terms are the generation capacity costs for nonparticipants and participants, respectively. The capacity savings is captured by the sixth term. Finally, the last term is the cost of the storage systems. Noting that $L^i = es^i$ for all participants, (2) can be re-written as

$$\pi = \sum_{i=1}^{n} [(p - b)(x_o^i + x_p^i) - \beta x_p^i]$$
$$+ \sum_{i=n+1}^{m} [(p-b)(x_o^i + x_p^i) - bs^i(1-e) + \beta e s^i(1-\alpha) - \beta x_p^i - C(s^i)] \tag{3}$$

To determine whether load management alone can increase profits, the utility is assumed to maintain the same price while installing the storage system. Note that if $s^i = 0$, then (3) reduces to the monopolist's profit without load management. If the derivative of π with respect to s^i evaluated at $s^i = 0$ is positive, then load management for the i^{th} consumer increases profit. This derivative is

$$\frac{\partial \pi}{\partial s^i} = (p - b)\left(\frac{\partial x_o^i}{\partial s^i} + \frac{\partial x_p^i}{\partial s^i}\right) - b(1 - e) + \beta e(1 - \alpha) - \beta\frac{\partial x_p^i}{\partial s^i} - C'(0) \quad (4)$$

To interpret (4), note that the i^{th} consumer's income is given by $I = I' + \alpha L^i\beta = I' + \alpha e s^i\beta$, where I' is income before participation and I is income after participation, which includes the incentive $\alpha L^i \beta = \alpha e s^i \beta$ For simplicity, we assume that peak and off-peak demands

are independent. The peak demand function is $x_p^i(p, I)$, so that

$$\frac{\partial x_p^i}{\partial s} = \alpha e\beta\frac{\partial x_p^i}{\partial I}$$

Similarly, for the off-peak,

$$\frac{\partial x_o^i}{\partial s} = \alpha e\beta\frac{\partial x_o^i}{\partial I}$$

Substituting (5) and (6) into (4) yields

$$\frac{\partial \pi}{\partial s^i} = \left[(p-b)\frac{\partial x_o^i}{\partial I} + (p-b-\beta)\frac{\partial x_p^i}{\partial I}\right]\alpha e\beta + \beta e(1-\alpha) - b(1-e) - C'(0) \quad (7)$$

The incentive offered to consumer i increases his income. If the income effect on demand for electricity is negligible, then

$\frac{\partial x_o^i}{\partial I} \simeq \frac{\partial x_p^i}{\partial I} \simeq 0$ and (7) reduces to

$$\frac{\partial \pi}{\partial s^i} = \beta e(1 - \alpha) - b(1 - e) - C'(0) \quad (8)$$

The first term is the marginal capacity cost savings of load management net of the incentive payment. The second term is the marginal cost of the addition kilowatt hours needed to satisfy peak demand taking into account the inefficiency of storage. These kilowatt hours are purchased during the off-peak, but for every unit purchased, only e units are brought into the peak. The last term is the marginal cost of adding a storage system. If (8) is positive, then load management for consumer i is profitable. That is, if the marginal cost savings in capacity of introducing storage exceeds the marginal costs of operating the storage system, the program should be introduced. The optimum sized system for customer i is given by s^{i*} that solves

$$\beta e(1 - \alpha) - b(1 - e) - C'(s^{i*}) = 0 \tag{9}$$

Figure 1 illustrates the solution.

If equation (9) holds for any i, then it will hold for all i, and all consumers can receive incentives while enhancing utility profits. That is, when income effects for all consumers are negligible, the utility's decision to introduce such a program is simply a matter of comparing the costs of storage with the operating and capacity costs of the utility.[6] Each consumer contributes the same to the increased profits, since each has an indentical storage system. That there should be no nonparticipants can be seen by using the Kuhn-Tucker condition with respect to n, the number of non-participants.[7]

$$\frac{\partial \pi}{\partial n} = s^n(b(1 - e) - e\beta(1 - \alpha)) + C(s^n) \leqq 0 \tag{10}$$

and

$$b(1 - e) - e\beta(1 - \alpha) \leqq -C(s^n)/s^n$$

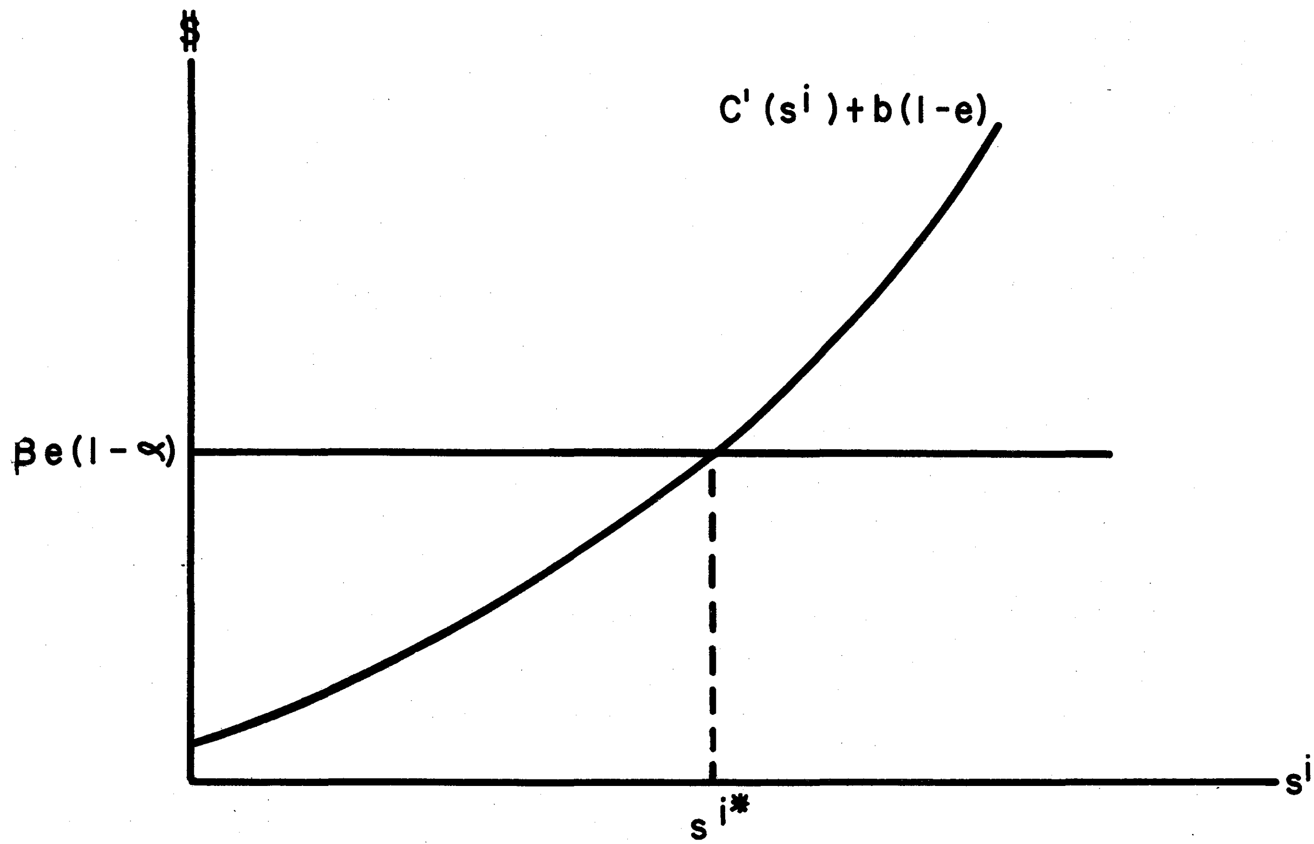


Figure 1

Determination of an Optimum
Sized System

Substituting from (9) yields

$$C'(s^n) \geqq C(s^n)/s^n \tag{11}$$

The left and right-hand sides of (11) are the marginal and average cost of storage, respectively. By increasing marginal cost, (11) is satisfied by strict inequality and n = 0 from (10) and Kuhn-Tucker conditions. Thus, the utility would want to have zero non-participants. From the consumers' prospective, there are no costs involved in participating, since they are all borne by the utility; therefore, full participation can be expected.

If enough consumers participate or s^{i*} is large enough, a shifting peak can occur. To ensure that storage is not installed to the point where the off-peak becomes a firm peak, the following constraint can be added to the profit-maximization problem.

$$\sum_{i=1}^{n} x_p^i + \sum_{n+1}^{m} (x_p^i - es^i) \geqq \sum_{i=1}^{n} x_o^i + \sum_{n+1}^{m} (x_o^i + s^i) \tag{12}$$

Using λ as a multiplier for (12), condition (9) for an optimum s^{i*} becomes

$$\beta e(1 - \alpha) - b(1 - e) - C'(s^{i*}) - \lambda(1 + e) = 0 \tag{13}$$

If $\lambda > 0$ so that constraint (12) is binding, then (13) implies that a smaller storage system is required for each consumer. In Figure 1, the horizontal line is lowered by $\lambda(1 + e)$, yielding an intersection to the left of s^{i*}. Each consumer still has an identical storage system, and the full capacity of the utility is utilized in both periods.

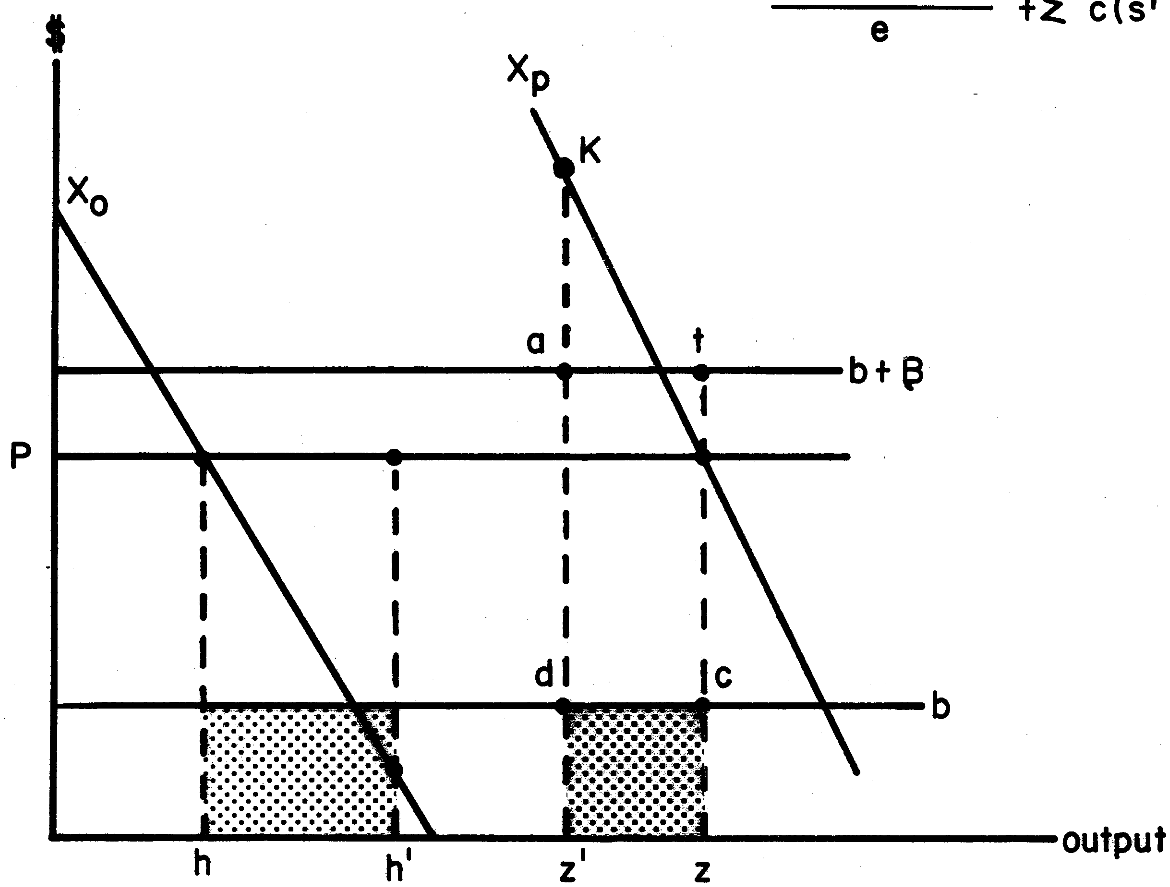
These solutions are straightforward when income effects are ignored. The utility can increase profits by replacing generating capacity with less expensive storage capacity. With increasing marginal cost of storage, there is a point beyond which additional storage is not worthwhile. This may occur before the peaks shift. If it occurs after, then storage is implemented until the period demands are equal. Figure 2 illustrates the benefits and costs of implementation for a non-shifting peak situation, holding price constant. Aggregate peak and off-peak demands are depicted by X_p and X_o, respectively. Generation capacity is reduced from z to z', where

$$z - z' = \sum_{1}^{m} es^{i*}$$

The consumers still receive output z during the peak, but z - z' of that output comes from storage. Storage is filled in the off-peak when consumers receive output h, plus h'- h, which is channeled to storage. Quantity h' - h must equal (z - z')/e because of storage losses. The benefits are given by Area atcd, which is the savings in capacity costs. The costs are Area dczz' divided by e, plus the costs of the storage facilities.

If income effects are not negligible, then the bracketed term in (7) plays a role. Assuming electricity is a non-inferior good, by (1) the first term in brackets is positive and the second term is negative. If the second term is large enough, therefore, a storage system is not effective in increasing profit. The incentive paid the consumer increases peak demand to the point where it offsets the savings in generating capacity afforded by storage. If the utility could discriminate among its customers, it should install storage where income effects are small, or even better, where they are negative. Thus, for non-negligible income effects, the utility may not want full participation, Benefits = area atcd

$$\text{Costs} = \frac{\text{area }(dczz')}{e} + \Sigma\, c(s^i)$$



$$h' - h = (z - z')/e$$

Figure 2

Benefits and Costs of Storage for Nonshifting Peak although all consumers would still want to participate because their costs are zero and they receive an incentive. Since the utility cannot determine the acceptable from the unacceptable consumers until after the system is implemented, implementation where the utility covers all costs may not be appealing to either the utility or society as a whole.

IV. Storage when the Consumer Covers the Cost

The preceding program places the costs of implementation on the utility. The utility pays for storage and provides incentives for participants. As an alternative, suppose the consumer is obliged to pay a storage fee or tariff to defray, in part or all, the cost of storage. Again, the consumer is not charged for the amount placed in storage that is lost to leakage (which raises some non-trivial billing issues). To provide an incentive for participation, the consumer pays a lower uniform price in both the peak and off-peak periods. Both the storage tariff and the lower price per KWH are dependent on the size of storage in that greater storage size means a larger price reduction but a higher tariff.

The uniform price charged to consumer i is given by $p - \delta s^i$, where δ is a proportionality constant which relates the price discount to the amount of storage. The storage tariff is given by γs^i. Profit from the i^{th} participant becomes

$$\pi^i = (p - \delta s^i - b)(x_o^i + x_p^i) + \gamma s^i - bs^i(1 - e) - \beta(x_p^i - es^i) - C(s^i) \quad (14)$$

From the utility's perspective, some storage for consumer i is profitable if the derivative of (14) with respect to s^i evaluated at $s^i = 0$

is positive. This derivative at $s^i = 0$ is

$$\frac{\partial\pi^i}{\partial s^i} = (p-b)\left(\frac{\partial x_o^i}{\partial s^i} + \frac{\partial x_p^i}{\partial s^i}\right) + (\gamma - \delta x_o^i - \delta x_p^i)$$

$$- b(1 - e) - \beta\frac{\partial x_p^i}{\partial s^i} + \beta e - C'. \tag{15}$$

To interpret this, note that demands are functions of prices and income,

$x_o^i(\overline{p}, p - \delta s^i, p - \delta s^i, I - \gamma s^i)$ and

$x_p^i(\overline{p}, p - \delta s^i, p - \delta s^i, I - \gamma s^i)$

where $\overline{p}$ is the price of other goods and p_o and p_p are the off-peak and peak prices, respectively, which are both equal to $p - \delta s^i$. For off-peak consumption

$$\frac{\partial x_o^i}{\partial s^i} = - \delta\frac{\partial x_o^i}{\partial p_o} - \delta\frac{\partial x_o^i}{\partial p_p} - \gamma\frac{\partial x_o^i}{\partial I} ,$$

Again, assuming independence between periods,

$\frac{\partial x_o^i}{\partial p_p} = 0$, and (16) becomes

$$\frac{\partial x_o^i}{\partial s^i} = - \delta\frac{\partial x_o^i}{\partial p_o} - \gamma\frac{\partial x_o^i}{\partial I}$$

$$= -\left[\delta\frac{\partial x_o^i}{\partial p_o} + \delta x_o^i \frac{\partial x_o^i}{\partial I}\right] + \frac{\partial x_o^i}{\partial I} (\delta x_o^i - \gamma)$$

$$= -S_o^i + \frac{\partial x_o^i}{\partial I} (\delta x_o^i - \gamma)$$

In (17), S_o^i is the Slutsky term for off-peak consumption, which is necessarily negative. A price decrease increases consumption and the increase in real income also increases consumption for a non-inferior good, so $-S_o^i$ is positive. A similar analysis yields for the peak

$$\frac{\partial x_p^i}{\partial s^i} = -S_p^i + \frac{\partial x_p^i}{\partial I}(\delta x_o^i - \gamma)$$

Substituting (17) and (18) into (15) and rearranging yields

$$\frac{\partial \pi^i}{\partial s^i} = (p - b)\left[\frac{\partial x_o^i}{\partial I}(\partial x_o^i - \gamma) - S_o^i\right] + (p-b-\beta)\left[\frac{\partial x_p^i}{\partial I}(\partial x_p^i - \gamma) - S^i\right]$$

$$+ (\gamma - \partial x_o^i - \partial x_p^i) - b(1 - e) + \beta e - C'(0) \qquad (19)$$

The last three terms in (19) are the same as (7) except there is no α in (19), since there is no payment to the consumer. Recall that to determine the optimal-sized system, (8) was obtained by assuming negligible income effects. In (19), income effects are again present, but now there are substitution effects as well. This follows, since now there is a price change as well as an income change and both income and substitution effects matter. If income effects are negligible, (19) becomes

$$\frac{\partial \pi i}{\partial s^i} = -S_o^i(p-b) - S_p^i(p-b-\beta) + (\gamma - \partial x_o^i - \partial x_p^i) - b(1-e) + \beta e - C'(0) \qquad (20)$$

In comparing this formulation to (8), where the utility covers costs of storage, and income effects are negligible, note that the first and second terms in (20) are positive and negative respectively. Consequently, no definitive statement can be made as to whether storage is more or less attractive to the utility when the consumer contributes to storage costs and receives a price reduction. The reason is clear, because (20) must be positive for the utility to opt for the program. Since off-peak price is above marginal running costs, additional consumption increases net revenues (from the first term). However, the second term contributes a negative sign. A greater peak Slutsky term (in absolute value) diminishes the utility's interest in participation, because the discount in the peak period price implies a greater quantity demanded at the peak and a concomittant lesser reduction in generation capacity. In other words, the greater the increase in peak quantity demanded as a result of the lower price, the less effective the program. The effectiveness is further diminished when peak period income effects are not negligible.

The third term in (20) is important as well. It measures the marginal net benefit of participation to the consumer, or the tariff minus the reduction in revenues paid via the unit prices. The utility has control over γ and δ, and would want to make the term as large as possible to increase profits (which increases the likelihood that (20) is positive). However, if it is positive, the consumer will not participate. That is, the utility can set (20) equal to zero and solve for an optimum s^i and present the new prices, tariff, and storage possibilities to the consumer, but the consumer will reject them unless

$$\gamma - \delta x_o^i - \delta x_p^i < 0 \tag{21}$$

Thus, (21) represents the trade-off for the utility: greater values for this term imply greater profits from the participants, but fewer participants if the program is voluntary.

To show that (21) must hold for consumer participation, consider the consumer's indirect utility function

$$\ell^i(\overline{p}, p - \delta s^i, p - \delta s^i, I - \gamma s^i)$$

Evaluating the derivative of ℓ^i at $s^i = 0$ yields

$$\frac{\partial \ell^i}{\partial s^i} = -\delta\frac{\partial \ell^i}{\partial p_o} - \delta\frac{\partial \ell^i}{\partial p_p} - \gamma\frac{\partial \ell^i}{\partial I}$$

By Roy's law, $\frac{\partial \ell}{\partial p} = -x \frac{\partial \ell}{\partial I}$, thus

$$\frac{\partial \ell^i}{\partial s^i} = (\delta x_o^i + \delta x_p^i - \gamma) \frac{\partial \ell^i}{\partial I} \tag{22}$$

Consumer i will opt for the program only if (22) is positive or the discount times consumption is greater than the storage fee, $\delta(x_o^i + x_p^i) > \gamma$. Alternatively, the consumer must have total peak and off-peak demands greater than γ/δ to participate.

Figure 3 illustrates the benefits and costs under the assumption of negligible income effects. During the peak, price drops from p to $p - \delta s$ and quantity demanded increases from x_p^i to $x_p^{i'}$. Quantity $x_p^{i'} - r$ is curtailed and comes from storage. The lined area near the peak demand represents social benefits, part of which is consumer surplus and part of which is cost savings for the utility. The crossed area under off-peak demand is benefits in terms of consumer surplus. Costs are the dotted area divided by e plus storage costs which are not pictured.

V. Summary and Conclusions

We have examined a utility-sponsored storage program with two different pricing options: 1) the utility covers storage cost and provides a lump-sum payment to the consumer as an incentive to participate, and 2) the consumer covers storage cost and receives a price discount as an incentive to participate. The cost of storage and the savings in generation costs were key terms in the utilities decision to adopt either option. Utilities typically consider these costs in their decisions, but do not always consider the feedback effects that lump-sum payments or price changes will have on demand. We included these effects to find that income effects from either lump-sum payments or

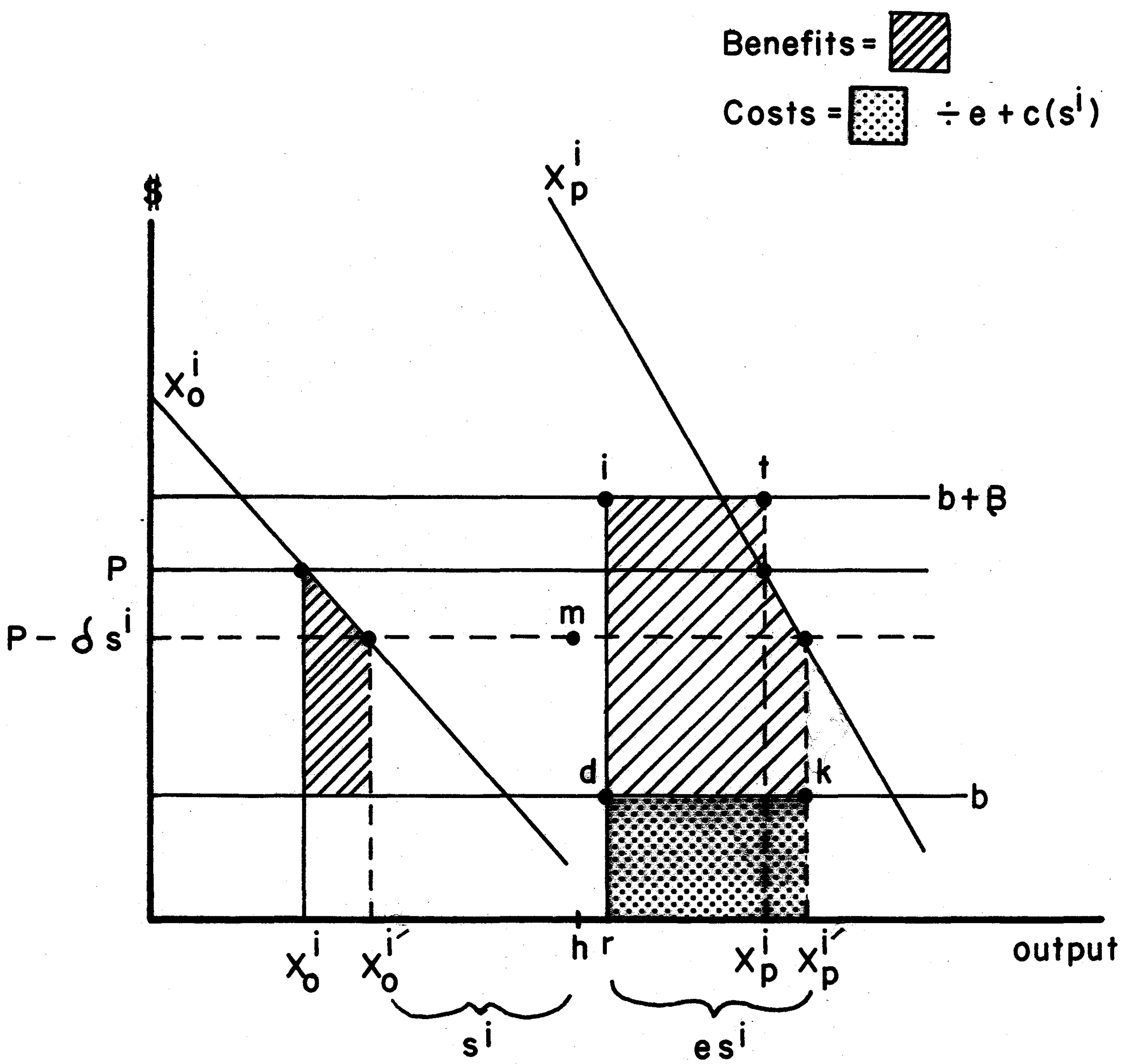


Figure 3

Benefits and Costs when Average Price Falls price declines will discourage the utility, since quantity demanded may increase during peak periods and thereby reduce the expected generation savings. In addition, substitution effects from a price decrease may discourage the utility if there is a significant increase in peak consumption.

Consumers will unquestionably participate under option one, because they are required to do nothing but receive a subsidy. Under option two, however, consumers will not participate unless the price discount makes up for the cost of storage.

The utility's problem of choosing among these two options and others is complicated by its lack of information. Cost data is available at current demand levels, but unavailable in the responsiveness of demand to the proposed changes. Of course, this is nothing unusual, and one of the important acitivities under PURPA was to improve demand estimation. Only after this is successful will utilities be able to confidently adopt storage systems.

From the standpoint of further research, several assumptions warrant additional attention. The simple model ignored uncertainty in peak and off-peak demands. The size of the optimal storage system will depend on this factor. In addition, the social benefits shown in Figure 3 reflect an assumption that the lower price induces additional consumption which <u>can be met</u> from storage. Alternatively, the discount could cause additional peak kwh consumption--which would offset some of the capacity savings (yielding a deadweight loss). Berg (1983) considered this problem in the context of direct load control.

Finally, what can the utility (and regulators) do about a customer who, to take an extreme case, only consumed kwh during the off-peak period. Under the first option, the consumer would happily accept an incentive payment to participate in the program. To get around this kind of problem, Nelson (1980) recommends that the incentive rate be defined in terms of other consumer and/or consumption characteristics. The point is that housing characteristics (such as insulation and appliance mix) and consumer behavior (including thermostat adjustments) need to be considered when implementing load management programs.

Notes

[1]Numerous U.S. utilities are experimenting with various types of storage systems for both residential and commercial customers. See the Summary of Utility Load Management Programs.

[2]Even the alternatives under thermal energy storage are complicated. Space heating and cooling and hot water heating represent the most likely applications of storage. The former is widely used in Europe. We abstract from a number of relevant issues, including the impact on the distribution system, the likelihood of improper sizing of storage systems, and uncertainty of electricity demand. Nelson (1980) addresses the implications of these problem for load management agreements and energy storage incentives.

[3]See Steiner (1957) and Williamson (1966) for well-known examples of the peak load literature.

[4]Note that in practice, utilities often ignore this problem--billing customers by total kwh consumed.

[5]This assumption masks some of the complexities of storage systems, but is similar to the system in Gravelle (1976). A somewhat more complex solar storage system is used in Hamlen and Tschirhart (1980).

[6]An implicit assumption in the solution to (9) is that $es^{i*} < x_p^i$, or optimum storage is not so large that it could supply all peak demand. If storage were extremely inexpensive, this assumption would not hold. Constraints could be appended to the problem to eliminate this possibility.

[7]Since n is a discrete variable, the derivative in (10) is an approximation of Leibnitz rule. We have ignored the possibility that there may be fixed costs of storage installation. If they are large enough, the utility may not opt or storage with small users.

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