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Electricity Wheeling and Incentive Regulation

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Abstract
This paper relates social contract regulation strategies to a particularly important comtemporary issue in energy regulation—electricity wheeling; we find that substantial gains in economic efficiency may be possible. First, social contracts give potential wheelers more monetary incentive than traditional regulatory procedures to provide wheeling services to interested third parties. Second, social contract regulation gives potential wheelers better incentives to measure marginal costs accurately. Third, under social contract regulation, wheelers have proper incentives to install efficient amounts of transmission capacity, thereby avoiding Averch-Johnson and other regulatory distortions that emerge in traditional regulation.

1. Introduction

In the last decade, regulators have begun to consider alternative methods of utility regulation to replace traditional cost-based regulation and its attendant inefficiencies. Under price-cap incentive mechanisms, regulators would determine a core set of utility services and specify a price ceiling either for each core service or for several composite indexes; price ceilings would be adjusted over time for expected productivity growth and inflation. So long as no price ceiling is exceeded, the utility may price services freely. Most significantly, if the utility can reduce costs, it may keep any resulting profits.

Price-caps and other forms of incentive regulation would be particularly useful when regulators cannot confirm the accuracy of a utility's reported cost data or when cost-based regulation offers utilities little incentive to behave efficiently; both conditions are often the case. An important emerging area in electricity regulation, the wheeling of third-party power by investor-owned utilities, may provide an appropriate niche for a modified price-cap incentive mechanism. Between 1973 and 1984, wheeling loads increased at an approximate annual rate of 12%, more than four times the corresponding annual rates for net generation and ultimate sales and more than three times the annual rate for resold electricity (Kaufman 1987, 27). This trend will surely continue as available generation capacity tightens and more efficient transmission technologies emerge. Furthermore, some individuals (most notably, Commissioner Charles Stalon (1988) of the Federal Energy Regulatory Commission (FERC)) have suggested more aggressive federal action to open transmission networks to independent sellers in order to develop a more efficient electricity network.

The wheeling issue presents several difficult problems for cost- based regulation (overviewed by Casazza (1985), Pfeffer (1985), Rosenzweig and Bar-Lev (1986)). First, investor-owned utilities may strenuously object to commission orders that they wheel third-party power across their service territory at prices designed only to recover costs (e.g., Edison Electric Institute (1988)). Second, since marginal transmission costs (especially *short-run congestion costs*) are difficult for regulators to measure, marginal cost-based pricing may be difficult to implement. Third, since spot-market price flexibility could be an economic way to ration access to a capacity-scarce transmission network, regulators may need to grant to the utility a certain degree of pricing flexibility. Fourth, if regulators set prices at short-run marginal cost, utilities may inefficiently underprovide transmission capacity in order to increase short-run congestion costs and their resulting profits; it would be very difficult for regulators to detect this practice.

This paper develops an incentive strategy for a regulated power company that offers two standard kinds of wheeling service, firm (reserved) and nonfirm (spot-market). Under the suggested strategy, the wheeling utility agrees to meet all buyer requests for firm power at negotiated contract prices. For nonfirm power, the regulator sets an average price ceiling that cannot be exceeded; subject to this ceiling, the utility prices nonfirm power along a uniform or nonuniform price schedule.

We shall consider three cases. First, under a *flexible uniform price*, the wheeler will undersize transmission capacity. Second, with *perfect information* and a perfectly *flexible nonuniform price schedule*, the chosen transmission capacity level will be economically efficient. However, because this second procedure requires instantaneous price flexibility of a nonuniform price schedule, it is not very practical. Third, we then allow wheelers to design only *one nonuniform price schedule* that cannot vary with demand conditions. Under this third option, we shall show that a profit-maximizing wheeler will size peak capacity and will price peak usage at nearly the same levels as would an economically efficient wheeler (subject to the same limits on price flexibility); the profit-maximizer will still overprice off-peak electricity. Without damage to the efficient capacity outcome, regulators may ensure that the nonuniform price schedule does not have excessive off-peak prices by imposing a price ceiling upon them.

The peak outcome is very significant. Although Averch and Johnson (1962) argued that regulated utilities may have incentives to overexpand their capacity, events in the past decade have evidently reversed this effect, as evidenced by the slowdown in generation construction. As capacity shortfalls are a particularly undesirable inefficiency that regulators must surely avoid, any regulatory mechanism should provide the economically correct signals for utilities to expand transmission capacity efficiently, especially if we envision (as we now do) an increasing reliance upon electricity wheeling to meet expected future electricity needs. Though we discuss electricity networks, the relevance of this paper to regulated communication systems and natural gas transmission is obvious.

This paper is set up as follows. Section 2 overviews the important legal and institutional issues that electricity regulators now face. Section 3 sets forth the notation, assumptions, and format of a basic model; Section 4 develops the important result that one nonuniform price schedule will induce a profit-maximizing wheeler to size its transmission capacity efficiently. Section 5 permits the regulator to prescribe a price ceiling in order to ensure fairness. Section 6 concludes the paper.

2. Institutional Issues

This section describes three important issues in the contemporary regulatory arena. The first concerns to what extent the FERC has the authority to order utilities to wheel power for third- party sellers. The second discusses how wheeling rates have been and could be set. The third discusses recent initiatives at the FERC toward deregulating wheeling prices.

Wheeling Authority

In *Otter Tail Power Company v. U. S.* (410 U.S. 366 (1972)), the United States Supreme Court upheld a District Court ruling that found that Otter Tail Power Company had attempted to monopolize retail distribution by, among other things, denying its municipalities access to other wholesalers; the Court enjoined Otter Tail from continuing these actions and required that the Federal Power Commission (FPC, which is now the FERC) establish wholesale and wheeling rates for Otter Tail at competitive levels. However, the Court also explicitly stated (410 U. S. 366, 375) that Part II of the Federal Power Act (16 U. S. C. 824 (b)), which granted the FPC its legal jurisdiction over interstate electricity transmission, does *not* grant the Commission the authority to order wheeling; the specific authority for the particular wheeling order for Otter Tail came instead from the Supreme Court's enforcement of the antitrust laws.

Congress passed the Public Utilities Regulatory Policy Act in 1978; Sections 203 and 204 became Sections 211 and 212 of the Federal Power Act. Section 211 gave the FERC the authority to order wheeling where it could conserve energy, improve efficiency, or increase network reliability (16 U.S.C. 824j(a)(2)). However, Section 212 stipulated several provisions including, most significantly, that wheeling orders must preserve "existing competitive relationships."

In a landmark hearing, *Southeastern Power Administration [SEPA] v. Kentucky Utilities Company*, 25 FERC 61, 204 (1983), the Commission considered SEPA's request to use its (i.e., FERC's) PURPA-granted authority to order Kentucky Utilities to transmit SEPA's power to eight municipalities. In making this decision, the Commission considered whether Congressional intent required that "existing competitive relationships" be assessed broadly over all municipal buyers or narrowly only over the eight affected municipalities; as the loss of eight municipalities would have a smaller comparable effect relative to the broader group of all municipalities, SEPA favored the broader and Kentucky Utilities the narrower interpretation. The FERC favored the narrow interpretation.

As a result of its SEPA precedent, the FERC has never compelled an unwilling utility to wheel power (Burns 1987, 66). Since the SEPA ruling, many parties have contended that the FERC has the legal authority to reinterpret Sections 211 and 212 more broadly and order wheeling more readily (e.g., from American Public Power Association, see Reinemer (1984) and Stockford (1984); also see Electricity Consumers Resource Council (1984)).

On June 2, 1988, FERC Commissioner Charles Stalon urged transmission access reform in a speech before the National Association of Regulatory Utility Commissioners; he envisioned "some sort of access regime on reasonably equal and efficient terms for suppliers of power to utility transmission grids." (Stalon 1988) In particular, Dr. Stalon suggested a broadened interpretation of "existing competitive relationships," deemphasizing the effect of wider transmission access upon any one customer's choice and attempting instead to preserve or enhance the competitive structure of the entire market. Simultaneously, the Commission invited comments on mandated conditional wheeling in a Notice of Proposed Rulemaking *Regulations Governing Bidding Programs*, Docket No. RM88-5- 000 (18 C.F.R. Parts 35 and 293).

Regulator-mandated wheeling does not sit well with the investor owned utilities, who claim that it jeopardizes the security of their transmission grids. If the FERC continues to become more aggressive, it must afford utilities incentives to open up their grids; these incentives would best offer the "carrot" of profits rather than any "stick." We then reach our first important consideration for regulatory reform; regulatory strategies for transmission wheeling must allow the utility the opportunity to make long-run profits.

Ratemaking Methods and Reforms

In two cases (*Cleveland Electric Illuminating Company*, 11 FERC 61, 114 (1980); *Otter Tail Power Company*, 12 FERC 61, 169 (1980)), the Commission adopted rolled-in ratemaking methods for wheeling rates that allocate the fully distributed costs of the integrated transmission system; it rejected alternatives that would have based wheeling rates upon directly attributable transmission costs. Under present ratemaking methodologies, rates for most wheeled power are derived by dividing allocated embedded costs by some measure of peak demand. A less popular alternative has been a split-savings approach; the wheeler receives 15% of the estimated net benefits of the power exchange while the other two parties split the remainder (*Interconnection Agreement between the Pennsylvania-New Jersey-Maryland Interconnection and the New York Power Pool*, Pennsylvania Power and Light Company, Rate Schedule FERC No. 66, Docket No. ER80-509).

In 1985, the FERC issued a Notice of Inquiry regarding possible avenues for reform, i.e., alternatives to embedded cost ratemaking, remedies for utility impediments to voluntary access, and auctions of excess transmission space. (*Regulation of Electricity Sales-for-Resale and Transmission Service*, Docket No. RM85-17-000 (Phase I)). A well-circulated National Regulatory Research Institute monograph (Kelly and Henderson 1987) further discusses price-reform, advocating that wheeling utilities give buyers a choice between firm (reserved) and nonfirm wheeling service. Buyers who are planning long-run investments may choose firm service, which should be priced at long-run marginal cost; each price would include a constant charge for transmission capacity use. Buyers who seek short-run economy purchases and who are willing to risk the uncertainties of the spot-market may choose nonfirm service, to be priced at short-run marginal cost, which includes both a running cost and a component for system congestion that may vary instantaneously. This spot-market pricing of electricity power, called *real time pricing*, has been prominently suggested by Bohn, Caramanis, and Schweppe (1984).

The difficulty with regulator-determined marginal cost pricing resides in measuring marginal cost; specifically, short-run marginal costs would appear particularly difficult for regulators to determine. This is because the short-run congestion cost component that reflects the shadow price of foregone usage should vary instantaneously with prevailing market conditions. If regulators cannot determine or monitor congestion costs accurately, wheeling utilities could overstate costs and/or underbuild capacity in order to keep estimated congestion costs up; as pointed out, the capacity shortfall would be especially problematic. (Measuring long-run marginal cost, which would involve quantifiable capacity-expansion costs, might be easier; there are system planning programs that can be used in this measurement (Westinghouse 1980).

Similarly, a split-savings rule, which would encourage all economic transactions if each party had perfect information regarding each other's relevant cost data, would encourage strategic misrepresentation otherwise. This is best illustrated with an example. Suppose two parties have a 50-50% split-savings rule, the buyer has an avoided cost of 6 cents per kWh, and the seller has a generating cost of 4 cents per kWh. If each were to report costs accurately, each would profit by 1 cent per kWh. However, if the seller were to convince the buyer that his true costs were 5 cents, he would profit by 1.5 cents.

We then reach an additional consideration for transmission reform. There is no reasonable way that regulators can accurately determine either a utility's instantaneous short-run congestion cost or its efficient capacity size; therefore, utilities can misrepresent short-run marginal costs and/or underbuild transmission capacity when profitable. Accordingly, regulators must institute strategies that give wheeling utilities an incentive to measure costs accurately, minimize them, and build transmission capacity efficiently in order to avoid long- run bottlenecks.

Auctions

In view of the problems identified in regulator-determined cost- based prices, several recent filings for wheeling prices at the FERC have incorporated modified incentive-based approaches, which allow the Commission to specify price ceilings in some places in return for price deregulation elsewhere. These procedures would seem especially resolved to let the market mechanisms determine the short-run congestion costs that are difficult for regulators to measure.

The Western Systems Power Pool (WSPP) is an interconnected network of fifteen utilities in six western states. On March 12, 1987, the FERC approved the pool's filing for a two-year experiment involving transmission access (Docket ER-87-97-001). Under the agreement, the utility must set aside a prescribed portion of available transmission capacity for firm wholesale/wheeling customers at negotiated ceiling rates; the remainder would be available to interested wheeling customers under auction-determined spot-market prices to be posted through an "electronic bulletin board" and subject to FERC-specified ceilings. (See Kemp (1987).) Stockholders could retain 25% of the profits from trade; ratepayers would get the remainder. In approving the experiment, the commission cited the possible benefits of additional competition, better information, and price flexibility to ration scarce capacity (which present-day fixed rate pricing does not properly allocate); it subsequently approved a similar auction in *Baltimore Gas and Electric*, 28 FERC 61, 096 (1987)).

Though perhaps a step in the right direction, auctions still have two difficulties. First, in many wheeling jurisdictions, there might not be enough potential buyers to form a workable market. Second, as will be demonstrated below, wheelers that control a bottleneck may have an economic incentive to underprovide transmission capacity in order to increase congestion costs and the resulting market-clearing prices; this action may be difficult or impossible to detect.

Flexible Pricing

After the WSPP filing, pool member Pacific Gas and Electric (PG&E) entered into a separate agreement with Turlock Irrigation District; the FERC held two separate hearings on these rates (*Pacific Gas and Electric Company*, Docket Nos. ER88-219- 000, ER88-219-001). In both cases, PG&E offered to establish two different wheeling services for Turlock. First, the company agreed to provide unlimited Reserved Transmission Service; requests for existing capacity are to be priced at average embedded costs and requests for new capacity are to be priced at long-run marginal cost. Second, the company would provide nonfirm Coordination Transmission Service, to be billed on a per kilowatt-hour of actual usage; these coordination prices would be subject only to a price ceiling.[1] PG&E then established similar transmission services for Modesto Irrigation District (*Pacific Gas and Electric*, Docket No. ER88-302-001).

The Turlock and Modesto cases exemplify a modified price-cap approach to transmission pricing where the utility offers reserved transmission service at fair prices (i.e., average embedded cost or long-run marginal cost) and nonfirm service at flexible prices that are capped at Commission-specified price- ceilings. A wheeling customer has unlimited access to reserved transmission service; it must pay for its reserved kilowatt capacity in advance and the wheeling utility must add more transmission capacity if necessary. The wheeler meets nonfirm demands at spot-market rates that could depend upon instantaneous demand conditions. Subject to the Commission's ceiling, nonfirm prices are flexible; this price flexibility serves to ration scarce transmission capacity. Section 3 considers the implications of this procedure and its ability to meet the important considerations identified above (i.e., utility profitability, cost revelation and efficiency, and efficient capacity sizing).

3. A Model of Incentive Regulation

This section develops the notation, assumptions, and structure of a model of an incentive mechanism for electricity wheeling regulation.

Buyer Demand

The wheeling utility has three kinds of transmission demands: native, firm, and nonfirm. We shall temporarily assume that the first two demands (represented by D and Q) are constant over time; their respective prices are assumed constant at regulator-determined prices (e.g., average embedded cost or marginal cost).

We assume that the buyer's demand curve for nonfirm power is negatively sloped and that its usage intensity varies instantaneously over time. (In the case of wheeling, the "buyer" would be more accurately described as the generator-customer pair that is seeking to secure access to the grid.) Let i represent the instantaneous intensity, which is assumed to be stochastic with distribution $F(i)$ and density $f(i)$; a and e represent the respective minimum and maximum levels of intensity i. Let $U_i(q) = U(q, i)$ represent the willingness-to-pay for usage q under intensity i; its associated demand curve is dU_i/dq and level of usage is q_i. We also assume that the buyer's demand curves at two different usage intensities do not cross one another, a commonly made assumption (e.g., Spence (1977), Faulhaber and Panzar (1978), Goldman, Leland, and Sibley (1984)); higher demand curves correspond to higher demand intensities.

Capacity, Prices, and Costs

When sizing capacity, the wheeling utility must first meet native and firm demands prior to serving any nonfirm load. Therefore, the relevant *capacity constraint* is $D + Q + q_i \leq K$, which can be reexpressed

$$q_i \leq W, \tag{3.1}$$

where

$$W = K - D - Q$$

$W = K - D - Q$ represents the capacity that is available for nonfirm wheeling loads.

We assume that the buyer always pays the flat-rate cost of accessing the wheeler's transmission grid. If the wheeling utility knew demand parameter i and the price schedule were instantaneously flexible with regard to spot-market conditions, it could modify its price schedule as i changes. Let $R_i(q)$ represent necessary payments for usage q under demand conditions i. The marginal price of usage q—$p_i(q)$—is the first derivative $dR_i(q)/dq$. The commission establishes a price ceiling of $p_{\max}$ for nonfirm usage; this means that the average per unit revenue cannot exceed this price ceiling. That is, for all nonfirm usage q,

$$R_i(q) \leq qp_{\max} \tag{3.2}$$

This is the *ceiling constraint.*

Transmission costs comprise both running and capacity components. The most important running costs that the wheeler faces are the line losses that result when electricity flows over its power lines; power typically flows over many lines simultaneously. When the wheeled power flows in the same direction as other loads on a particular line, line losses increase, thereby increasing generation costs. However, if the wheeled power flows in the opposite direction, both line losses and associated generation costs decrease (Kelly and Henderson (1987)). The incremental cost of line losses that result from a megawatt-hour of wheeled power is the sum of the losses that result on each line and necessarily depends upon the exact configuration of loads at any instant; it can be positive or negative.

The marginal cost of a power flow may also include appropriate compensation to neighboring utilities whose transmission networks inadvertently carry some wheeled power, due to the unavoidable flow over many circuits. Additionally, minor running costs include reactive power generation, operation expenses, and equipment depreciation.

Regarding capacity costs, the wheeler can expand transmission capacity in a number of ways; in order of increasing costs, these ways would include adding capacitor banks to control reactive power, installing additional circuits, upgrading voltage on existing lines, and constructing new facilities. (See Kelly and Henderson (1987, pp. 87-177, passim).) We shall always assume that a wheeler incurs costs along its minimum cost envelope. In addition to permitting more power flow during the peak hour, capacity increases may affect line losses at all hours; as transmission capacity increases, line losses (i.e., running costs) would move closer to zero. At any moment, the marginal effect of this incremental capacity cost varies with the size and direction of load on the wire.

Given these engineering relationships, we symbolically represent the total costs of the grid under demand conditions i as $C(Q + q_i, D, K)$. Under conditions i, the marginal cost of line losses associated with an increment of wheeled power is $c_i = C_1$, where C_1 represents the derivative of cost C with respect to its first argument; if wheeled power flows in the same (opposite) direction of native load, $c_i > (<) 0$. Consistent with electrical engineering theory, we assume that the second derivative of line losses with respect to usage is positive (Westinghouse 1980); i.e., $C_{11} > 0$.

At a nonfirm wheeling usage of q_i, the associated marginal cost of an increment of transmission capacity would be $k_i = C_3$; this would include both the cost of the additional transmission capacity equipment and the incremental effect of capacity upgrades upon instantaneous line losses under demand conditions i. Since usage q_i is stochastic with distribution $F(i)$, the marginal cost of capacity is then $k = \int_a^e k_i \, dF(i)$.

Flexible Real Time Pricing: Uniform Rates

We now consider the first of three cases; the wheeler has perfect knowledge of the buyer's demand parameter i and flexibility in setting rates, which are uniform at any point in time. As defined, $U_i(q) = U(q, i)$ represents the buyer's willingness-to-pay for usage q under conditions i, which may vary instantaneously; larger levels of U are associated with higher values of i. Letting $p_i = p(q_i)$ represent the marginal price of usage q_i, a necessary condition for the buyer's optimal q_i is

$$p_i = \frac{\partial U_i}{\partial q} \tag{3.3}$$

We shall maintain this buyer's optimizing condition throughout, with both uniform and nonuniform prices $p(q_i)$.

Under the circumstances, a welfare-maximizing wheeler would set its instantaneous price p_i to maximize joint benefit $\int_a^e [U(q_i, i) - C(Q + q_i, D, K)] \, dF(i)$ subject to (3.3) and the constraint of (3.1) that instantaneous usage $q_i \leq$ available wheeling capacity W. A relevant Lagrangian is then

$$L = \int_a^e [U(q_i, i) - C(Q + q_i, D, K) - m_i[q_i - W]] \, dF(i) \tag{3.4}$$

m_i is a Lagrangian coefficient that restrains q_i to be less than available wheeling capacity W.

Differentiating with respect to quantity q_i, using (3.3), and appropriately solving (with a * to represent a welfare-maximizing solution)

$$p_{i*} = c_{i*} + m_{i*} \tag{3.5a}$$

Differentiating with respect to capacity W and solving

$$\int_a^e m_{i*} \, dF(i) = \int_a^e k_{i*} \, dF(i) = k_*. \tag{3.5b}$$

From (3.5a), a welfare-maximizing wheeler would set price p_{i*} at short-run marginal cost, which would include marginal running cost c_{i*} plus the coefficient m_{i*}; i.e., $p_{i*} = c_{i*} + m_{i*}$. The coefficient m_{i*}, which reflects a Lagrangian constraint on capacity utilization, would be positive (zero) if system usage were at (below) full capacity. Let $I(m_{i*})$ represent an indicator variable that takes on a value of 1 if $m_{i*}>0$ and 0 otherwise; i.e., $I(m_{i*})$ is positive (zero) when system usage is at (below) full capacity. From (3.5a-b), a welfare-maximizing wheeler should expand its transmission capacity until the resulting expected marginal increase in social surplus that is made possible by the additional transmission capacity just equals the expected capacity cost; that is, $\int_a^e [p_{i*} - c_{i*}]\, I(m_{i*})\, dF(i) = \int_a^e k_{i*}\, dF(i)$.

Assuming that price p_i varies with demand conditions i but is constant for all purchases q_i at each i, a profit-maximizing wheeler would attempt to maximize its expected profits $\int_a^e [p_i q_i - C(Q + q_i, D, K)]\, dF(i)$—subject to (3.1) and (3.3). The Lagrangian is now

$$L = \int_a^e [p_i q_i - C(Q + q_i, D, K) - m_i[q_i - W]]\, dF(i) \tag{3.6}$$

Differentiating (3.6) with respect to q_i and W produces the profit-maximizing first-order conditions; the absence of a * subscript indicates the profit-maximizing solution

$$mr_i = c_i + m_i \text{ and} \tag{3.7a}$$

$$\int_a^e m_i\, dF(i) = \int_a^e k_i\, dF(i) = k \tag{3.7b}$$

where

$$mr_i = p_i + \left(\frac{\partial p_i}{\partial q_i}\right) q_i = p_i(1 + \frac{1}{E_i})$$

E_i represents the own-price elasticity of demand q_i under conditions i.

From (3.7a), a profit-maximizing wheeler sets the price p_i at the point where marginal revenue mr_i equals short-run marginal cost $c_i + m_i$. As before, the Lagrangian coefficient m_i in (3.7b) would be positive (zero) if system usage q_i were at (below) available system capacity W; let $I(m_i)$ be an indicator variable that equals 1 if $m_i > 0$ and 0 if $m_i = 0$. From (3.7b), the utility would add capacity until the expected marginal profit that is made possible by the new capacity just equals the expected marginal capacity cost; i.e., $\int_a^e [mr_i - c_i]\, I(m_i)\, dF(i) = \int_a^e k_i\, dF(i)$. Comparing (3.5a-b) and (3.7a-b), a profit-maximizer undervalues—by the amount $p_i - mr_i$—the social benefit of an additional kilowatt of capacity; consequently, it underbuilds transmission capacity.

Flexible Real Time Pricing: Nonuniform Rates

If the wheeler could design a system of nonuniform price schedules with instantaneous

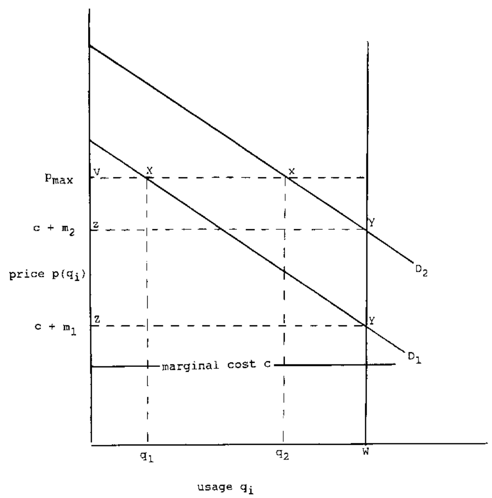

Figure 1. Demand curves and marginal cost.

price flexibility and knowledge regarding demand parameter i, the above inefficiency would vanish. To see this, consider figure 1; let D_1 and D_2 represent the demand curves under two possible states i. A regulator-imposed price ceiling is $p_{\max}$, which is assumed to exceed the maximum short-run marginal cost (i.e., $c + m_2$). If the wheeler were to observe perfectly the demand curve D_1 (D_2), he could implement a nonuniform schedule that prices the first q_1 (q_2) mWh at the ceiling level $p_{\max}$ and the remaining $W - q_1$ ($W - q_2$) mWh nonuniformly along the demand curve D_1 (D_2); under both schedules, the last mWh evidently would be priced at short-run marginal cost $c + m_i$. The resulting schedule then involves first-degree price discrimination at each point in time, truncated at the top by a price-ceiling at $p_{\max}$. Assuming that each of the two demands occurs half the time, profits would be the sum $(VXYZ + Vxyz)/2$.

When sizing transmission capacity with the nonuniform price schedule, the profit-maximizing wheeler would have an incentive to add transmission capacity until the expected marginal profit that is made possible by an incremental unit of capacity just equals its expected marginal cost. Because changes in any one price do not necessarily affect any other price in a nonuniform price schedule, this condition is represented by $\int_a^e [p_i - c_i]\, I(m_i)\, dF(i) = \int_a^e k_i\, dF(i)$. This outcome is evidently economically efficient, as would be expected under first-degree price discrimination.

Note that if $p_{\max}$ were set below any market clearing price (e.g., the marginal cost $c + m_2$)—the efficient outcome could not result. Thus, regulators must be careful not to constrain the wheeler's upward price flexibility in the vicinity of full capacity; a simple way around the problem is to relax all price constraints within a certain neighborhood of peak capacity.

Though this approach is economically efficient, it is very impractical, as it requires perfect wheeler knowledge of demand and instantaneously responsive nonuniform pricing. We shall now consider a more practical alternative that restricts price flexibility but that still may produce an efficient capacity decision.

4. Results: Imperfect Flexibility

We now allow the wheeler to offer a nonuniform price schedule $R(q)$ that *cannot* vary as the demand parameter i changes; as will be shown, transmission capacity will be efficiently sized.

We now permit native loads D to vary instantaneously; let I represent the prevailing demand intensity. Reasonably, demand intensities I and i can be expected to be conditional upon one another; let $g(I \mid i)$ and $G(I \mid i)$ represent the respective Bayesian density and distribution of I given parameter i. The respective minimum and maximum of demand intensity I are A and E. Expected wheeler profits are then the difference between expected revenues and associated costs

$$p = \int_a^e \int_A^E [R(q_i) - C(Q + q_i, D_I, K)] \, dG(I \mid i) dF(i) \tag{4.1}$$

The wheeler must maximize profits subject to the capacity constraint (3.1) and the ceiling constraint (3.2), which are now expressed

$$q_i + D_I + Q \leq K \tag{3.1'}$$

$$R(q_i) \leq p_{\max} q_i. \tag{3.2'}$$

Additionally, the wheeler faces the constraint that a profit- maximizing buyer selects usage in (3.3).

A relevant Lagrangian is then

$$L = \int_a^e \int_A^E R(q_i) - C(Q + q_i, D_I, K) - m_{Ii}[q_i + D_I + Q - K] \, dG(I \mid i) dF(i)\}$$

$$- \int_a^e \int_A^E n_{Ii}[R(q_i) - p_{\max} q_i] \, dG(I \mid i) \, dF(i) \tag{4.2}$$

In this section, we shall assume that the ceiling constraint of (3.2) is not binding; therefore, $n_{Ii} = 0$. (4.2) can be reexpressed with a reversal of integration formula (Spence 1977):

$$L = \int_a^e [p_i - \overline{c}_i - \overline{m}_i] \, [1 - F(i)] \, di \tag{4.3}$$

where

$$\overline{c}_i = \int_A^E c_{Ii} \, dG(I \mid i) \text{ and}$$

$$\overline{m}_i = \int_A^E m_{Ii} \, dG(I \mid i) \, .$$

We differentiate (4.3) with respect to price p_i and solve

$$p_i = \bar{c}_i + \bar{m}_i + \frac{1 - F(i)}{f(i)\dfrac{\partial i}{\partial p}} = \bar{c}_i + \bar{m}_i + \frac{\partial^2 U}{\partial q \partial i}\left[\frac{1 - F(i)}{f(i)}\right]. \tag{4.4}$$

The second equality follows from (3.3) (i.e., $\partial U_i/\partial q = p_i$); we shall use (4.4) in the analysis below. A related objective function and first-order condition appear in Spence (1977).

There is an easy intuitive explanation behind (4.3) and (4.4). Regarding (4.3), price p_i is the marginal revenue for usage at usage level q_i; any changes in it would affect buyer revenues only when the prevailing demand parameter j weakly exceeds i; i.e., $q_j \geq q_i$. Therefore, $1 - F(i)$ represents the probability S_i that changes in p_i affect wheeler profits. Using this reasoning, capacity-constrained profits from price p_i can be expressed as the difference between price and marginal cost (i.e., $p_i - \bar{c}_i - \bar{m}_i$) times the probability S_i that the particular marginal profit is operational; i.e., $S_i = 1 - F(i)$. Total profits are the integral over all possible demand parameters i (i.e., $\int_a^e [p_i - \bar{c}_i - \bar{m}_i]\,[1 - F(i)]\,di$); this appears in (4.3).

(4.4) evidently can be rewritten

$$\frac{p_i - \bar{c}_i - \bar{m}_i}{p_i} = \frac{1 - F(i)}{p_i f(i)\left(\dfrac{\partial i}{\partial p}\right)}. \tag{4.5}$$

Since $\partial S_i/\partial p = -f(i)(\partial i/\partial p)$, the elasticity of probability S_i with respect to changes in price p_i is evidently $[\partial S_i/\partial p]\,[\partial p_i/\partial S_i] = -p_i f(i)\,(\partial i/\partial p)/[1 - F(i)]$. Therefore, (4.5) is a simple inverse elasticity rule for a profit-maximizing firm.

If demand parameters i and I were perfectly correlated with one another, the Bayesian density $g(I \mid i)$ would be degenerate. Under these circumstances, (4.4) would simplify

$$p_i = c_i + m_i + \frac{\partial^2 U}{\partial q \partial i}\left[\frac{1 - F(i)}{f(i)}\right]. \tag{4.6}$$

Analysis: Degenerate Case

We begin the analysis with the degenerate case represented by (4.6).

A profit-maximizing nonuniform price schedule must terminate at marginal cost for the largest demand parameter e; for no other reason, if the price schedule were to intersect the demand curve D_e (which corresponds to the largest intensity e) at a price that exceeds marginal cost, the wheeler could induce further usage and increase profits simply by pricing along the demand curve D_e until price equals marginal cost. More technically, in (4.6), $F(i) = 1$ for the largest intensity e; therefore, $p(q_e) = c_e + m_e$ is the appropriate price at endpoint q_e.

For $i < e, F(i) < 1$. Since demand curves do not cross one another, $\partial U/\partial q$ is a monotonically increasing function of demand intensity i; therefore, $\partial^2 U/\partial q \partial i > 0$. From (4.6), the wheeler would price all usage prior to level q_e above marginal cost. Therefore, if marginal cost were constant (i.e., $c_i = c$) and no constraints binding (i.e., $m_i = n_i = 0$), schedule $ACEH$ in figure 2 would be a representative price schedule; the schedule need not be monotonically downward-sloping, but I shall assume that it is. Since most vendors usually like to give price discounts, not hikes, to larger usage levels, a downward-sloping schedule seems evident.

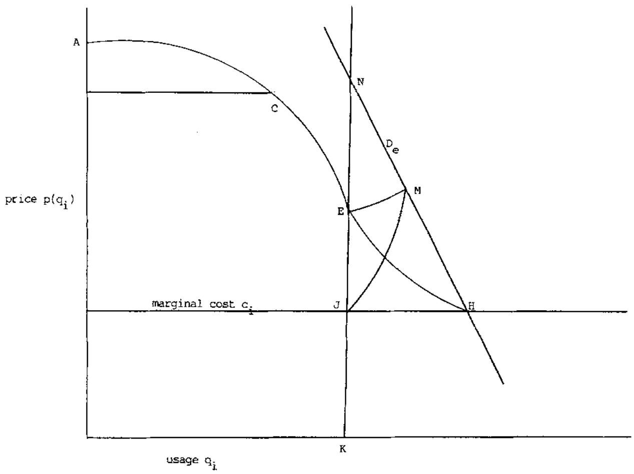

Figure 2. Nonuniform price schedule with constant marginal cost.

Evidently from (4.6) and figure 2, the price schedule $p(q)$ includes a markup over marginal cost. Therefore, if the marginal cost schedule were to bend upward at usage levels to the right of point J, the price schedule $p(q)$ should be affected at points to the right of point E; $ACEM$ then represents a reasonable price schedule for an upward-sloping marginal cost curve. By this reasoning, if the marginal cost curve were to become vertical at point J (as happens with a binding capacity constraint at K), $ACEN$ would be a relevant price schedule. Therefore, the price schedule would become completely vertical at point E if a binding capacity constraint were present at K.

To this moment, we have assumed that marginal cost is horizontal prior to full capacity. Figure 3 illustrates how the cost and price schedules change allowing for an upward-sloping marginal cost curve prior to full capacity. Intuitively, a nonuniform price schedule is a form of first-degree price discrimination based on an expected demand curve; the expectation is assessed over the distribution $F(i)$. This ability to price discriminate accounts for the downward-sloping price schedule prior to full capacity. Once buyer demands reach the capacity constraint, all uncertainty regarding the level of usage vanishes; at this point, it makes sense to price the next increment of usage as high as possible, which means the

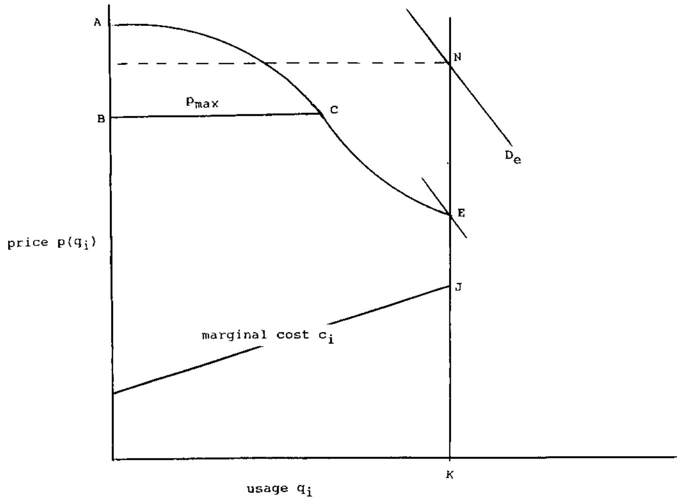

Figure 3. Nonuniform price schedule with increasing marginal cost.

market-clearing price.

The Capacity Level

For a fixed nonuniform price schedule in figures 2 or 3, if transmission capacity K were increased by one megawatt, usage to the left of full capacity points E or J would not be affected; only at usage levels that are at full capacity can additional profit inflow result. Consequently, a profit-maximizing wheeler would expand capacity until its expected marginal profits from an additional megawatt just equal its expected marginal capacity cost; i.e., $\int_a^e [p_i - c_i]\, I(m_i)\, dF(i) = \int_a^e k_i\, dF(i)$. For a welfare-maximizing wheeler (to be subscripted by a *), off-peak usage would be priced at marginal cost c_{i*} and on-peak usage at $c_{i*} + m_{i*}$. Consequently, it would expand capacity until $\int_a^e [p_i - c_{i*}]\, I(m_{i*})\, dF(i) = \int_a^e k_{i*}\, dF(i)$. The two conditions are evidently similar, and under most practical circumstances a welfare-maximizer will select the same capacity as a profit-maximizer with the same degree of pricing flexibility.[2]

Complications

If the parameters I and i were not perfectly correlated with one another, the density $g(I \mid i)$ would be stochastic; (4.4) would become relevant. The equation includes the terms $\overline{c}_i$ and $\overline{m}_i$, which are averages of c_i and m_i, integrated over the distribution $G(I \mid i)$. Thus, they are expected marginal costs for any value of i; price p_i is a markup over these expected marginal costs $\overline{c}_i + \overline{m}_i$. Mutatis mutandis, a profit-maximizing and an efficient wheeler would both still expand capacity until expected marginal profit from an additional kilowatt of capacity just equalled marginal capacity cost.

5. The Price Ceiling Constraint

Wheeling advocates may object to a nonuniform price schedule that permits the wheeler unlimited flexibility to price its service. Regulators may handle this concern by imposing a price ceiling constraint at $p_{\max}$, which is presumed to be fair. From (3.2), the necessary constraint is $R(q_i) \leq p_{\max}q_i$.

We can now consider a ceiling constraint at $p_{\max}$ without any formal math. In order to avoid interfering with the market-clearing process during peak usage, we shall assume that regulators do not enforce any price constraint on p_i when the system is operating within a reasonable vicinity of the full capacity level. If the price schedule were monotonically decreasing and a ceiling constraint added at $p_{\max}$, the schedule would be topped off at the ceiling level; therefore, schedule *BCEN* would become relevant (see figure 3).

But for its trivial effect upon off-peak line losses (see footnote 2), the lower price ceiling during off-peak hours does not change the basic optimizing conditions for system capacity; consequently, the profit-maximizing firm still efficiently chooses its capacity level, as in Section 4. Furthermore, regulators can change the ceiling price to conform to different notions of fairness; as long as market-clearing prices during peak hours are not affected, the chosen capacity level would be efficient.

The PG&E-Turlock experience suggests two candidates for the price ceiling. One possible candidate for a price ceiling is a multiple of long-run marginal cost, which may be more easily determined than short-run marginal cost; planning models that measure the former are available (Westinghouse 1980, passim). Alternatively, regulators may determine average embedded cost using any number of fully distributed cost methods more designed to determine "fair" prices than efficient ones. Footnote 1 contains more possibilities. The choice between the options hinges on the choice between efficiency and fairness; regulators must ensure that the resulting level is sufficient to allow the wheeler a reasonable profit for its effort.

If regulators were to specify a price ceiling $p_{\max}$, the wheeler could keep any resulting profits if it could lower marginal costs; with regulatory lag, this would represent a short-run gain. It could potentially turn into a long-run gain if regulators were to commit to adjusting the price-ceilings for expected general cost inflation and productivity growth but not for changes in actual costs and productivity; this would eliminate any future linkage between costs and prices. Under these circumstances, if the utility were to lower its costs, it would keep the profits; if its costs were to increase, it would suffer the consequences.

6. Conclusion

We conclude this paper by summarizing the approach and advantages of our incentive strategy. Regulators must specify two prices, a fixed price for reserved wheeling demands and a price ceiling for nonfirm; this ceiling can realistically be based upon some multiple of long-run marginal cost or average embedded cost. Subject to these constraints, the wheeler may design one nonuniform price schedule for nonfirm wheeling. Four advantages consequently arise. First, the possibility of long-run profits may afford wheelers the economic incentives to open up their transmission network and provide wheeling service that large customers now desperately want. Second, regulators do not need to establish prices based on short-run marginal costs or to attempt to ensure that wheelers minimize costs; provided that price ceilings are adjusted for expected productivity-adjusted cost inflation (and not actual costs), wheelers have the appropriate incentives both to measure costs accurately and to minimize them. Third, wheelers do not modify their price schedule to meet instantaneous variations in the buyer's demand parameter; although they ideally would like to do so in order to maximize profits, such flexibility in a nonuniform price schedule is not very realistic. Finally, a profit-maximizing wheeler will have incentives to size transmission capacity as efficiently as would a welfare-maximizing wheeler with the same degree of price flexibility. This result is quite satisfying; without regulator surveillance, the mechanism induces a profit-maximizing utility to behave efficiently without requiring an impractical degree of price flexibility.

This approach is not without problems however. First, profit- maximizing wheelers will price off-peak usage above marginal cost, thereby inefficiently restricting buyer demands during these periods. Second, particular arrangements may give wheeling customers uneconomic incentives regarding the choice of firm and nonfirm wheeling contracts. Third, determining profit-maximizing schedules can get difficult if many wheeling customers appear; auctions might be easier, albeit flawed, alternatives when there are many wheeling customers. Finally, regulators may feel politically compelled to restrict wheeling prices during peak periods; this would have a depressing effect upon the wheeler's chosen capacity level.

Notes

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1. The price ceiling would be the highest of (1) the sum of four specific subfunctionalized transmission rates (System Interconnect, Generation Tie, Backbone, Area), (2) 50% of the difference between PG&E's and Turlock's production expenses, and (3) PG&E's highest filed rate for a similar transmission service.

2. Though the two maximizing conditions look similar, a welfare- maximizer theoretically has a slight incentive to invest differently than a profit-maximizer. This results because the welfare-maximizer prices lower during off-peak hours and consequently generates more usage during these hours. As pointed out in Section 3, increments in capacity affect line losses that are associated with instantaneous usage; because usage levels would differ, incremental line loss savings would as well. This difference can be positive or negative, depending in which direction the wheeling load flows. However, this theoretical difference would not be a significant practical problem under most circumstances since wheeling loads usually account for less than 10% of a utility's total transmission load and nonfirm wheeling is some fraction of this.

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