Chapter 72

ELECTRIC POWER MARKET DESIGN ISSUES AND LABORATORY EXPERIMENTS

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The incentive failure of government ownership of public utility industries has helped to motivate the worldwide privatization of these industries (Smith, 1996). Similar shortcomings of rate-of-return regulation in the United States has led to major changes in the way in which the gas, telephone and cable TV industries are regulated, as public policy has leaned toward, if not fully embraced, the substitution of markets for direct regulation of these industries. Radical technological changes in long distance communication and transmission have also contributed to this accelerating trend. The United Kingdom prominently denationalized electric power in 1991, providing a model for other countries in deciding how (and how not) to create a competitive electric power industry. Since the UK was among the first, the effort was marred by shortcomings, which largely represented political compromises that were most likely unavoidable. Littlechild (1995) provides a recent review of the UK experience. New Zealand, Australia and many other countries initiated the process of privatizing/deregulating their electric power industries. Australia began trading spot power on an interstate grid in the southeast region of the continent in the autumn of 1998. The Energy Policy Act of 1992 set the stage for deregulating the industry in the United States, and major reforms in the current regulatory system are well underway, California's being among the most prominent.

Here are only a few of the many economic design questions that dependably arise in the typical country's debate on competition in producing electrical energy: (1) What should be the rules governing the bidding process in the spot market? (2) How many independent generator companies are required for competition? (3) How should transmission be structured and priced? (4) Should there be demand side as well as supply side bidding in the spot market? (5) How does excess base load capacity (inflexible must-run generators) affect market performance? (From Australia to California off-peak spot prices are sometimes near or equal to zero.) (6) How does the existence of large must-serve inelastic loads impact market performance? (7) How can markets be used to provide both energy reserves and energy supplies in complex multi-node networks?

In the first entry below we use experimental methods to study (1) and (3) in a regime in which the number of independent generators is not systematically varied and in which extensive interruptible demand side bidding is considered (based on Backerman, Rassenti, and Smith, 2000). The spot auction mechanism we use is the Uniform Price Double Auction (UPDA) studied in a simple one-node supply and demand environment by McCabe, Rassenti, and Smith (1993), and implemented by the Arizona Stock Exchange. Initially we examine transmission pricing and income shares on the basis of short-run marginal cost (energy loss) in transmission lines, with a residual congestion

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price, based on network opportunity costs, when a line is loaded to capacity. This allows us to focus entirely on the technical and behavioral question: Who receives the congestion rents when a line is capacity constrained? Based on engineering optimization models, it has been assumed that congestion rents will be collected by the line owners (Bohn, Caramanis, and Schweppe, 1984). But such analysis does not deal with the question of how bidding behavior may be affected by line constraints; nor does it ask if optimization is supported by an equilibrium model. We also inquire as to how market efficiency and the income shares of producers, wholesale buyers, and transmission line owners are altered with a variation on the auction market bidding rules. The effects of a line constraint and of changing the auction market rules are both examined under different levels of experience on the part of the subjects.

The second entry examines questions (6) and (7) in the above list within a six-period repetitive demand cycle environment in a nine node network with eight demand/supply centers (based on Olson et al., 1999). An experimental study of (2), (5) and (6) is reported by Denton, Rassenti, and Smith (2001).

1. Nodal Price Theory for Lossy Lines

In this section we provide a very brief introduction to the engineering economics of electric power supply and transmission that are used in the experimental designs underlying the two essays to follow.

Energy flows in transmission lines are subject to resistance that causes energy loss in the sense that energy is dissipated in the form of heat in the transmission conductor, and is therefore unavailable to do work at the delivery end of the line. For simplicity we derive the optimal pricing rules using a two-node network. The principles, however, apply to multinode, multiple generator and multiple buyer networks.

If X megawatts (one thousand kilowatts or one million watts) of power per unit of time (power is a time rate of energy flow) are injected into the input buss on the line, then $Y < X$ megawatts per unit of time are withdrawn from the output buss. Since the line loss, $L(X)$ is approximately a quadratic function of injected power, we have

$$Y = X - L(X), \quad L(X) \cong aX^2. \tag{1}$$

If $B(Y)$ is the benefit function for Y units of power delivered to buyers, and $G(X)$ is the supply cost of generators injecting power into the line, the standard engineering optimization problem for an interior maximum is

$$\max_{X,Y>0} B(Y) - G(X) - \lambda\bigl(Y - X + L(X)\bigr), \tag{2}$$

where λ is a Lagrange multiplier. The marginal conditions for an interior maximum point (X^0, Y^0) in (2) are

$$\lambda = B'\bigl(Y^0\bigr) = \frac{G'(X^0)}{1 - L'(X^0)}, \tag{3}$$

where $L'(X)$ is the marginal transmission loss (MTL), and $1/(1 - L'(X))$ is the transmission 'loss factor' used to adjust the marginal cost of generation, $G'(X)$, for line losses.[1] The 'system lambda' (λ) measures the marginal cost of generation, after adjustment for transmission loss, at the delivery buss where marginal value is $B'(Y)$. Henceforth we drop the superscript zero, but it will be understood that we are dealing with optimal quantities.

Letting $P_B = B'(Y)$ be the delivered price of power, and $P_G = G'(X)$ be the price of generated power, then from (3)

$$\frac{P_B - P_G}{P_B} = \frac{B' - G'}{B'} = L' \cong \frac{2L}{X} = 2ATL, \tag{4}$$

where $ATL = L/X$ is the average unit transmission loss of power. The percentage decrease in price from the delivery to the injection node is simply the percentage marginal power loss in the line, which is approximately twice the average percentage loss. Thus, if the average loss in the line is 5%, and the price at the delivery node is normalized to unity, $P_B = 1$, then the generator node price $P_G = 1 - 2(.05) = 0.9$, 90% of the delivery price. These principles generalize to any network with losses $L_{ij}(X_i)$ on line ij with power X_i injected at i and power Y_j extracted at j (see Bohn, Caramanis, and Schweppe, 1984). At peak loads long lines – for example in New Zealand from the South Island to the top of the North Island – can dissipate 15% or more of the injected power.

Note that buyer expenditures total $P_B Y$, while generator revenues total $P_G X$. The revenue imputed to the transmission line is the difference, which by substitution from (1), (3) and (4) can be written

$$\begin{aligned} R_T = P_B Y - P_G X &= \left[P_B(X - L) - P_B(1 - L')X\right] \\ &= P_B\left[(XL' - L)\right] \cong P_B L. \end{aligned} \tag{5}$$

The line receives optimal revenue equal in value to the losses (it does not "receive" the losses) evaluated at the delivered price. The imputed "price" of the transmission line (per unit of injected power) is then

$$P_T = \frac{R_T}{X} = \frac{P_B L}{X} \cong P_B ATL. \tag{6}$$

[1] More precisely, with multiple wholesale buyers, $B_i(y_i)$, $i = 1, \ldots, n$ and multiple generators, $G_j(x_j)$, $j = 1, \ldots, m$, we have in place of (2)

$$\max_{x_i, y_i > 0} \sum_{i=1}^{n} B_i(y_i) - \sum_{j=1}^{m} G_j(x_j) - \lambda\left(\sum_{i=1}^{n} y_i - \sum_{j=1}^{m} x_1 + L\left(\sum_{j=1}^{m} x_j\right)\right).$$

Then for an interior maximum (3) becomes

$$\lambda = B_1'(y_1) = \cdots = B_n'(y_n) = \frac{G_1'(x_1)}{1 - L'(X)} = \cdots = \frac{G_m'(x_m)}{1 - L'(X)}.$$

If any buyer, i, is inactive, then $B_i'(0) < \lambda$ for that buyer; if any generator, j, is inactive then $G_j'(0) > \lambda(1 - L'(X))$ for that generator.

If the transmission line has a capacity constraint, K, then the criterion (2) becomes

$$\max_{X,Y>0} B(Y) - G(X) - \lambda\bigl(Y - X + L(X)\bigr) - \mu(X - K). \tag{2'}$$

The last term expresses the opportunity cost caused by congestion when the capacity constraint is binding.

For a maximum point (X^0, Y^0),

$$\lambda = B'\bigl(Y^0\bigr) = \frac{G'(X^0) + \mu}{1 - L'(X^0)}, \quad X^0 = K,\ Y^0 = K - L(K). \tag{3'}$$

Transmission revenue corresponding to (5) is then

$$R_T = P_B Y - P_G X = P_B\bigl(KL'(K) - L(K)\bigr) - \mu K \cong P_B L(K) + \mu K. \tag{5'}$$

The imputed price of transmission is therefore

$$P_T = P_B ATL(K) + \mu, \tag{6'}$$

which is the value of the average energy lost plus the unit opportunity cost incurred because of congestion.

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References

Backerman, Steven, Rassenti, Stephen J., Smith, Vernon L. (2000). "Efficiency and income shares in high demand energy networks: Who receives the congestion rents when a line is constrained?" Pacific Economic Review 5 (3), 331–347.

Bohn, Roger E., Caramanis, Michael C., Schweppe, Fred (1984). "Optimal pricing in electrical networks over space and time". RAND Journal of Economics 15, 360–376.

Denton, M., Rassenti, S., Smith, V. (2001). "Spot market mechanism design and competitivity issues in electric power". Journal of Economic Behavior and Organization 44, 435–453.

Littlechild, Stephen (1995). "Competition in electricity: Retrospect and prospect". In: Beesley, M.E. (Ed.), Utility Regulation: Challenge and Response. Institute of Economic Affairs, London, pp. 101–114.

McCabe, Kevin A., Rassenti, Stephen J., Smith, Vernon L. (1993). "Designing a uniform-price double auction". In: Friedman, D., Rust, J. (Eds.), The Double Auction Market Institutions, Theories, and Evidence. Proceedings, vol. XIV, Santa Fe Institute. Addison–Wesley, Reading, MA, pp. 307–332.

Olson, M., Rassenti, S., Smith, V., Rigdon, M., Ziegler, M. (1999). "Market design and motivated human trading behavior in electricity markets". In: Proceedings of the Thirty-Second Annual Hawaii International Conference on System Sciences, vol. 3. IEEE Computer Society Press, Washington, DC, pp. 3022–3039.
Smith, Vernon L. (1996). "Regulatory reform in the electric power industry". Regulation 1, 33–46.