TRANSMISSION CONSTRAINTS, INCENTIVE AUCTION RULES AND TRADER EXPERIENCE IN AN ELECTRIC POWER MARKET

STEVEN BACKERMAN, STEPHEN RASSENTI and VERNON L. SMITH

1. Experimental Network Environment

The lower panel in Figure 1 displays a simple 3-node radial network underlying the experiments we report herein. Wholesale buyers, B(4), with the number of independent buyers denoted in parenthesis, are located at the center node. Three generators are at the left node, G1(3), and three at the right node, G2(3). Each generator node is connected to the buyer node by a single transmission line, T1(1) and T2(1). In this case T1 and T2 have no active agents quoting transmission prices which are computed using (6) or (6′) from Backerman, Rassenti, and Smith (2000). The transmission function is served passively; i.e., revenue accruing to a line is a residual rent. This network provides a very simplified, aggregated, representation of the United Kingdom grid. London is at the center, and is by far the dominant buyer node. The major generation complex is to the north of London with the power lines bringing power into the London metropolitan region subject to constraint when winter peak demand is heavy. A smaller generation complex is to the south of London where there are controversial proposals to locate new generation capacity on the coast.[1]

The last line printed in Figure 1, labeled Eq., states a competitive equilibrium for a particular parameterization of this network (see below). The right-hand side (hereafter RHS) displays the equilibrium with 49 units of power (e.g., 490 megawatts) being injected at a price of 202.2 at node G2 by three generators. At the buyers' node B, four wholesale buyers receive 42.5 units delivered by T2 from G2 at price 275.

Applying the principles of section I on the RHS line we have $ATL_2 = L(X_2)/X_2 = (49 - 42.5)/49 = 0.13235$, and therefore $MTL_2 = L'(X_2) \cong 2ATL_2 = 0.2647$. With price 202.2 at G2, we verify that $P_B = P_{G2}/[1 - L'(X_2)] = 202.2/(1 - 0.2647) = 275$. From (6) the equilibrium price imputed to T2 is $P_{T2} = P_B ATL_2 = 36.3$. (All calculations are subject to rounding errors.)

On the LHS, the calculations must take into account that T1 is constrained with capacity $K = 29$, so that $X_1 \leqslant 29$. The three generators at G1 inject 29 units into T1 and 24.1 units arrive at B from the LHS. The average loss of power on T1 is therefore $ATL_1 = L(X_1)/X_1 = (29 - 24.1)/29 = 0.1689$, with marginal

[1] This sketch is based on conversations between Rassenti and Smith and the UK Office of Electricity Regulation (OFFER) in 1994.

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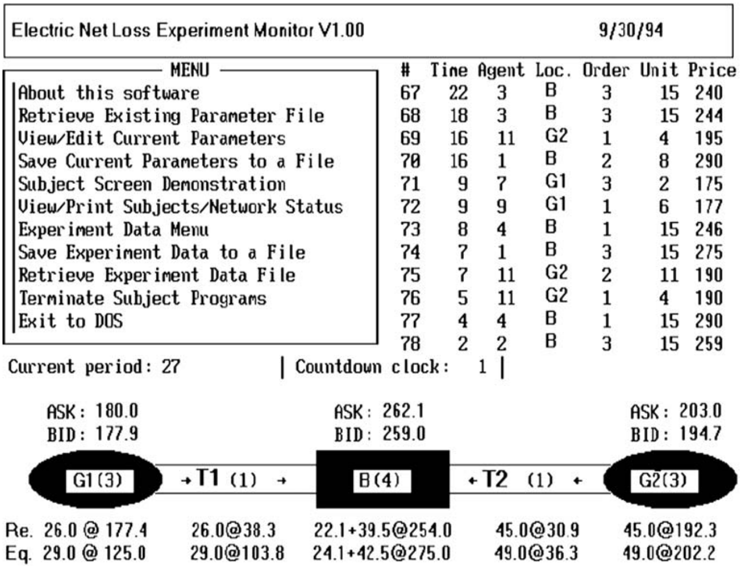

Figure 1. The monitor screen for the three-node radial network, used in the electric power experiments reported below, has two remote generator nodes G1 and G2 (shown as ovals) each with three generation companies, and a central load center at node B (shown as a rectangle), with 4 wholesale buyers. The line labeled Eq. on the bottom left shows a competitive equilibrium: 29 units of power at price 125 is injected at G1. The constrained (flow $\leqslant$ 29) transmission line T1 accepts the 29 units for transfer at price 103.5 to B. At B, 24.1 units arrive (loss $= 29.0 - 24.1 = 4.9$) from G1. Reading from the right, at G2, 49 units are injected at price 202.2. The unconstrained line T2 accepts the 49 units at transfer price 36.3. At B, 42.5 units arrive from G2, where buyers pay the delivery price 275. The line labeled Re shows the actual flows and prices for period 27 (middle left) for one experiment with 1 second shown remaining on the countdown clock (center of figure). Immediately above the network is displayed the standing bid and ask at each node. In the experiments reported below subjects see only the bid and ask at their own node. The upper right display exhibits the most recent order flow items #67–#78 in period 27. Thus at time 22 (seconds remaining) agent 3 at location B submits her 3rd order to buy, 15 units at limit price 240, which is subsequently improved (displaced) at time 18 by the higher bid price 244.

loss $MTL_1 = L'(X) \cong 2ATL_1 = 0.3379$, where $X_1 = K$ is optimal under constraint. $P_B = B'(K - L(K)) = 275$, and $P_G = G'(K) = 125$ we have $275 = (125 + \mu)/(1 - .3379)$ and therefore $\mu = 57.1$. Consequently, from (6′) in Backerman, Rassenti, and Smith (2000), $P_{T1} = P_B ATL_1 + \mu = 275(.1698) + 57.1 = 103.8$, showing how $P_B ATL_1 + \mu$, the congestion rental price of a constrained line, can soar relative to marginal loss. This also suggests why the regulation, or ownership, of electrical utilities by political entities does not use opportunity cost principles in pricing transmission networks. In this case the unit opportunity congestion cost is over two times the marginal loss price. Of course the economic function of these congestion rents is to signal the need for investment – investment to increase the transmission capacity of T1, to increase low cost generation capacity at node G2, or to introduce demand side management technologies that will conserve energy consumed by buyers at B.

In the top right panel of Figure 1, column 1 shows messages (orders to buy or sell) 67 through 78 sent by agents to the control center. Column 2 shows the time remaining, in seconds, when each message arrived. Columns 3–5 identify respectively the agent, his/her location, and the order number for that agent. The last two columns show the quantity in units and unit price specified in the order. On the first line below the top panels is shown the current period number (27), and the seconds remaining (1) on the countdown clock for that period. Immediately above the G1, B and G2 nodes is the standing bid/ask state of the market at each node. It is important to note that each agent sees only the bid/ask spread at his/her own node. This is primarily because the subjects have enough to do without trying to observe bids and asks at all nodes. We expect, however, to run experienced subject experiments with all this information displayed on each subject's monitor screen. All the nodal bids and asks do appear on the experimenter's monitor screen, but not the bid/ask state of the two transmission lines. We have added these for the display in Figure 1. Since the transmission price is given by Equation (6), we apply (6) (see Backerman, Rassenti, and Smith, 2000) to the ask at B to get the ask for T1 (T2) and to the bid at B to get the bid at T1 (T2).

The equilibrium price and quantity calculations, illustrated above, are based on marginal losses $L'(X^0)$ where X^0 is the last unit injected at a generator node. But the bid and ask prices at each node are computed for an additional unit added to the flow if a new trade occurs at the quoted bid or ask. For example consider the G1 node where the best unaccepted current ask price by one of the G1 generators is 180. What asking price does this translate into at the buyer's node, after correction for losses? To determine this look at the data for the current realizations appearing on the second line from the bottom in Figure 1, labeled "Re." Note that 26 units of power will be the injection at G1 based on the current state of the market. The ask of 180 is for one additional unit, which would make the injection rate 27 units of power. Since the coefficient of loss is 0.0058 on the left (not shown) we have a marginal loss of $L'(27) = 2(0.0058)27 = 0.3132$. Therefore the marginal transmission factor is $1 - L'(27) = 0.6868$. It follows that the asking price at B corresponding to an ask of 180 at G1 is $180/0.6868 = 262.1$ as shown.

Now look at G2 where the best ask by a generator is 203. The coefficient of loss on T2 is 0.0027 (not shown). Since the current tentative injection rate at G2 is 45, we have $1 - L'(46) = 0.7516$ and the ask at B corresponding to an ask at G2 of 203 is $203/.7516 = 270.1$. This is higher than the asking price at B for power coming from G1 which, as computed above, was 262.1. The optimization algorithm requires the ask at B to equal $\min(262.1, 270.1) = 262.1$, as shown in Figure 1.

In like manner we can compute the bid at G1 which corresponds to the standing bid of 259 at B. As above the marginal transmission factor on line 1 is 0.6868 and from (3) the bid at G1 is $.6868(259) = 177.9$. Similarly the bid at G2 is $.7516(259) = 194.7$. If some generator lowers an unaccepted offer to less than this locational adjusted bid, he/she is guaranteed to increase his/her volume of trade.

Table 1

The experimental design uses a 2 (auction rule variations) by 2 (LHS constrained or not) by 2 (experience level, once, ×, or twice, × ×) design. Ten inexperienced training sessions are not included. The entries n (m) under the × and × × columns indicated the number of experiments (n) and periods (m). Under the Other-side rule, as soon as at least one bid and offer has been provisionally accepted in the supply/demand cross a new bid (offer) arriving in real time cannot displace any inferior bid (offer) standing in the cross until it first meets the terms of an offer (bid) on the other side of the market. Consequently, at any time t, all bids and offers in the (provisionally accepted) cross earn conditional time priority. In the Both-sides rule, any bid (offer) that is higher (lower) than a bid (offer) in the cross immediately replaces the latter. Note that the left-hand side (LHS) transmission line is constrained at 29 units in nine experiments, unconstrained in 9 experiments

Auction rule	Left-hand side (LHS) constrained	Experiment ×	Experiment × ×
Both-sides	Yes	2(27)	1(28)
			1(25)
Both-sides	No	2(28)	2(28)
Other-side	Yes	1(23)	1(28)
		2(28)	1(29)
Other-side	No	1(23)	2(29)
		1(24)	
		1(27)	

2. Experimental Design

Our experimental design is summarized in Table 1. We report 18 experiments (10 experienced, and 8 twice experienced subjects) using 100 subjects in total. Subject payout averaged \$34 per subject per experiment. The supply, demand and transmission loss environment is illustrated in Figure 2 for our two treatments: when neither T1 nor T2 is constrained and when only T1 is constrained. All subjects were first run in initial "training" sessions to familiarize them with the environment and the spot market trading procedures. This data is not reported and has not been examined. When subjects returned for the second (experienced) sessions, and for the third (twice experienced) sessions from 23 to 29 trading periods were completed. In these sessions subjects were free to review the instructions again but most of the two-hour sessions were devoted to trading.

3. The Mechanism: A Continuously Updated Nodal Uniform Price Auction

We employ a 3-node version of the Uniform Price Double Auction (UPDA) studied in McCabe, Rassenti, and Smith (1993). In fact the mechanism used here is identical to the one cited if the asking prices at G1 and G2 are all adjusted for marginal transmission losses, and thus represent delivered prices at the reference buyers' node. We use the following UPDA rules that, under test, were favored among the many alternatives discussed and studied in McCabe, Rassenti, and Smith (1993, pp. 309–316).

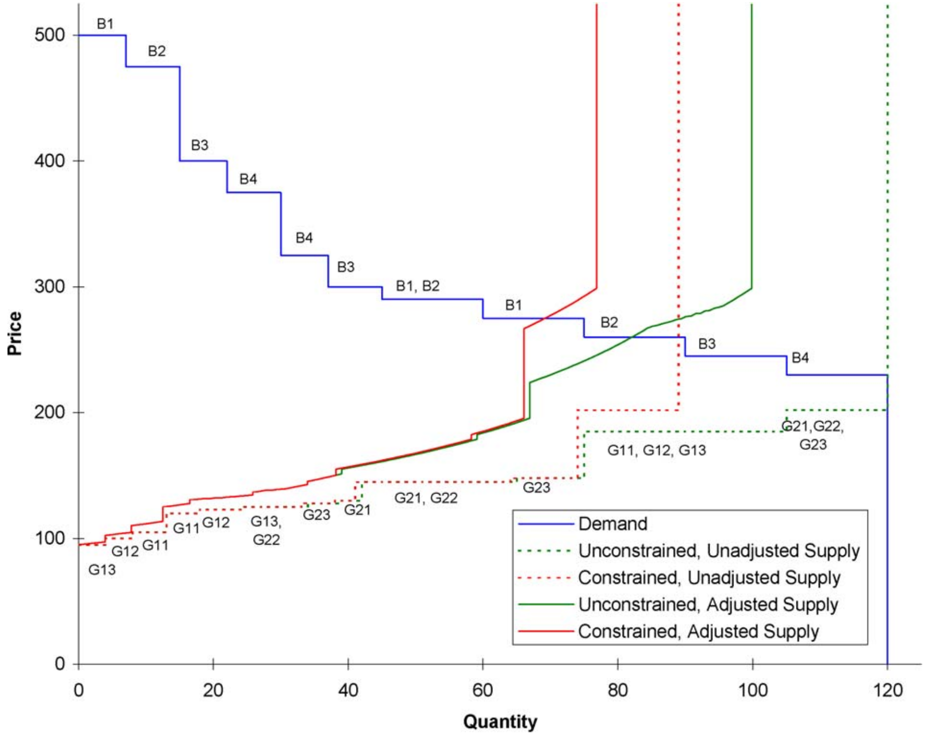

Figure 2. The generator supply schedule, and load demand schedule illustrate the induced supply-demand environment. All prices are computed (loss adjusted) at the B (buyer) reference node. Each of four buyers have three demand steps; interruptible at the price levels shown or lower at the buyer's discretion who is contractually bound to receive no higher resale price. Each generator step, denoted G_{ij}, refers to generator node $i(= 1, 2)$ and generation owner $j(= 1, 2, 3)$. At each node, each generation company has three generators whose marginal cost is indicated by the vertical level of the step. The unadjusted generation cost schedules are shown dashed, while the supply, adjusted for transmission loss to node B, is shown as a solid line. In each case the smaller supply (higher cost) schedule applies when the LHS line is constrained, the larger supply schedule is for the LHS unconstrained.

1. Call Rule. The market is called at the end of a preannounced period of time. Each period in these experiments closed after 4 minutes.
2. Message Rule. An agent's order is acceptable if it is a new order or improves the price terms of the last order submitted: bids must be at a higher price, or demand more units, while offers must be at a lower price, or supply more units. The price improvement requirement captures one important feature of the continuous double auction rules used widely in financial markets.
3. Update rules (for explicit details see McCabe, Rassenti, and Smith, 1993, pp. 312–315);

(i) The Both-sides rule: allows any agent to beat the terms of accepted orders (displace them) on his/her own side of the market (buying or selling), or meet the terms of an unaccepted order on the other side, whichever is best for the agent submitting the order. For example if the highest accepted offer is \$9, and a new order to sell at \$8 is entered it replaces the accepted offer at \$9.

(ii) The Other-side rule: agents must meet the terms of unaccepted bids or asks on the other side of the market to become accepted. This rule assigns temporary time priority to orders tentatively accepted; i.e., an accepted bid (ask) cannot be displaced by an unaccepted bid (ask) until that order has met the terms of an unaccepted order on the other side of the market. In the previous example the new offer at \$8 does not automatically replace the accepted offer at \$9. It will do so only when the standing unaccepted bid by a buyer exceeds \$8, but does not exceed \$9. If it exceeds \$9, then both the bid and the offer are accepted.

(iii) The tentative price at each node, or for transmission capacity, is uniform for all agents at that location (or on that line), and represents a clearing price for all accepted bids and asks at that point in time.

McCabe, Rassenti, and Smith (1993, p. 320) report that the other-side rule increases efficiency relative to the both-sides rule. Why? A buyer (seller) can enter the demand and supply (bid/ask) cross with an accepted bid (offer) only by meeting the terms of a seller (buyer) unit that is currently unaccepted. This provides an incentive for buyers and sellers outside the cross to meet each other's terms, increasing the chance that there will be an increase in volume traded and therefore in efficiency. It also undercuts the incentive to wait until near the period's end to enter bids (offers). The other-side rule recognizes a form of temporary time priority; i.e., a bid (offer) that is accepted has priority over later ones – even those that provide better terms – unless such orders yield new trades with the other-side. The other-side rule is especially efficient at overcoming price inertia when initial trades are off equilibrium: it accelerates price discovery. Figure 1 provides a snapshot of the price pressure the other-side rule provides. Notice the standing bid (259) is above the current trading price (254) but below the standing ask (262.1), so the owner of this bid is not trading because lower accepted bids have higher priority. This puts strong upwards price pressure on this buyer that will tend to move the market-clearing price toward the competitive equilibrium (275).

4. Hypotheses and Tests

We use the following regression equations to measure the effect of the experimental treatment variables on efficiency and the income share of each agent class:

$$Y_{i,t} = \alpha + \beta Y_{i,t-1} + \beta_1 D_1 + \beta_2 D_2 + \beta_3 D_3 + \varepsilon_{it},\quad i = 1, 2, 3, 4;\ t = 1, 2, \ldots, T; \tag{1}$$

where T = number of trading periods; $D_1 = 1$, if subjects are twice previously experienced and $D_1 = 0$, if subjects are once experienced; $D_2 = 1$ if the LHS transmission line is constrained, $D_2 = 0$ if the LHS is unconstrained; $D_3 = 1$, when the other-side auction rule applies, and $D_3 = 0$, when the both-sides rule applies. The dependent variables, Y_{it}, include total market efficiency, G1 profit share, B profit share and G2 profit share, respectively in each of four different regression equations, $i = 1, 2, 3, 4$. The lagged dependent variable, $Y_{i,t-1}$, is included to correct for expected significant auto correlation in each time series. The profit shares are all normalized with respect to the competitive equilibrium predicted share. Thus, if the buyer's share is 1.1 this indicates that they are receiving 110% of their competitive equilibrium share.

We test three a priori hypotheses.

HYPOTHESIS 1. Increased subject experience will increase efficiency.

This prediction is based on previous experimental findings in which experience is sometimes found to significantly increase total subject earnings. The null alternative argues that in some contexts attempts at manipulation may emerge with experience, which may yield a negative impact on efficiency, but increased profit for some subjects.

HYPOTHESIS 2. The effect of the constraint on line T1 will be to increase the share of income accruing to the upstream generators, G1.

When a line is constrained the demand for energy injected at the upstream node becomes perfectly inelastic for all generator node price increases from $P_G = G'(X^0)$ up to $P_G = G'(X^0) + \mu$ as in Equation (3′) in Backerman, Rassenti, and Smith (2000). The supply also becomes perfectly inelastic for all price decreases from $P_B = G'(X^0) + \mu$ down to $G'(X^0)$. In between there are a great many non-cooperative equilibria depending upon the configuration of extra marginal generation and demand steps. Since in the present design we have no generator agent excluded at prices above $G'(X^0)$, we expect G1 subjects to effect a substantial increase in the G1 node price. There is nothing insidious (or collusive) about this expected increase in generator prices. To control for this the subjects are not informed at any time that T1 is constrained at 29 units.

HYPOTHESIS 3. Efficiency, using the other-side rule, will be greater than under the both-sides rule.

As noted in Section 4 this is because the other-side rule provides better incentives for those buyers and sellers, who are outside the cross at any time, to agree on their respective terms of trade. Such agreement is a precondition for subverting the temporary time priority afforded those units which currently have acceptance status. This also provides incentives to enter into contracts early in the period to gain some time priority.

Table 2
A regression analysis of measures of market performance on experience level (once or twice previously experienced), whether the LHS transmission line is constrained or not, and the Other-side versus Both-sides auction rule, yields the indicated results. Thus efficiency increases (not significantly) with experience level, decreases (significantly) when the LHS line is constrained and increases (significantly) with the Other-side rule

Performance measure	Effect of treatment on performance measure		
	Experience	LHS line constraint	Other-side auction rule
Efficiency	Increases	Decreases[a]	Increases[a]
G1 profit share	Decreases[a]	Increases[a]	Increases[b]
B profit share	Increases[a]	Decreases	Increases
G2 profit share	Decreases	Increases	Increases[a]

[a]Significant, $p < 0.001$.
[b]Significant, $p < 0.01$.

5. Regression Results

Table 2 summarizes the regression results using all the experiments listed in Table 1. The results support Hypothesis 1 but it is not significant, while Hypothesis 3 is strongly supported; i.e., efficiency is increased significantly by the other-side rule. Hypothesis 2 is also supported: under the T1 line constraint the upstream generators at G1 raise their offers and gain an increase in their share of the surplus. We also observe the prior unpredicted result that the T1 constraint significantly lowers efficiency. It would appear that strategic behavior by the generators on the left, when they face a line constraint, also interferes with the achievement of efficiency. Also as expected from Hypothesis 3 is the observation that the G1 (also G2) generators gain a significant increase in surplus under the other-side rule. The buyers also gain, but the increase is not significant. All these classes of agents enjoy an increased (Pareto improving) share of surplus (relative to the competitive equilibrium prediction) because the other-side rule increases efficiency by 5.5 percentage points (not shown). More surplus is available and all agents receive an increase in earnings.

6. Further Results

In this section we report charts for one experiment which illustrate the regression results, and provides the reader with a visual representation of the dynamics of an experiment, which is imperfectly captured in the regression report of the previous section.

Figure 3 plots the period-by-period results for an experiment with twice-experienced subjects, operating under a T1 line constraint. In this figure an observation of 1 means 100% of the competitive equilibrium share of the surplus for some class of agents –

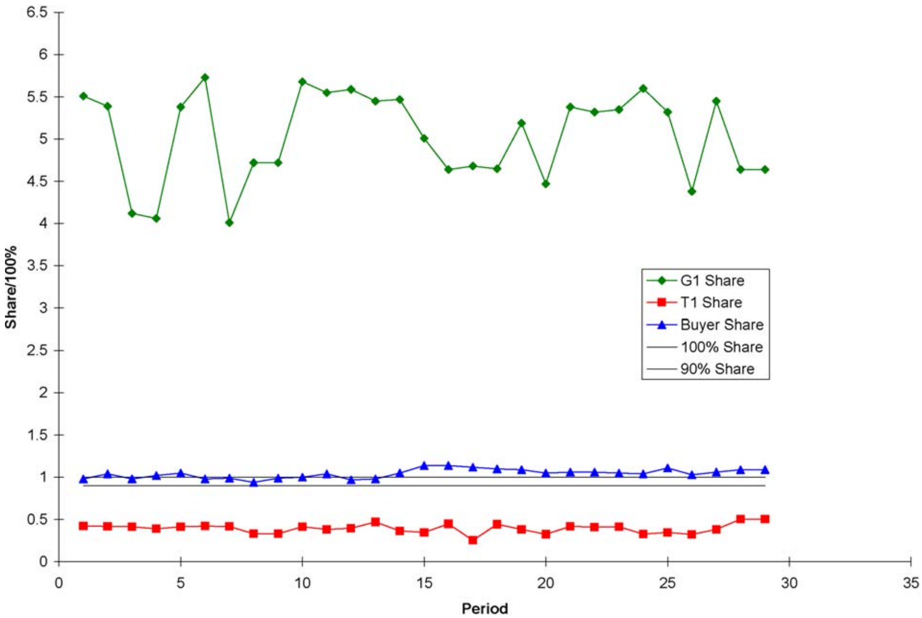

Figure 3. The share of realized surplus obtained by buyers, all generators at G1, and imputed to the constrained line T1, are plotted in the chart for each trading period 1 through 29. (Experiment 9283CXX.) Each observation on share is charted as a proportion of the benchmark competitive equilibrium imputation to each agent class. Thus the buyers' share hovers around 100% of the CE prediction until period 15, then rises slightly. The T1 transmission share is 50% or less than the CE prediction. This leads to a greatly enlarged share for the three generators at node G1, who receive some 400–500% of the CE imputation. Consequently, much of the congestion rent that would accrue to the constrained line, T1, if the generator and buyer node prices were competitive, is transferred to the upstream generators at G1, who raise their offer prices, increasing the price at G1 much above the CE bench mark.

buyers, generators, transmission lines. Not shown is total efficiency which is very high: 95 to 100%.

Figure 3 shows very clearly that: (1) buyers capture very little of the congestion rents from the LHS constraint; (2) generators at G1 capture much of these congestion rents; (3) these shares are extracted directly from the transmission share. Thus, G1 agents average about 500% of their predicted equilibrium share of the surplus while transmission line T1 receives less than half of the rents imputed to it at the competitive equilibrium.

7. Conclusions

Our conclusions can be summarized as follows:

1. The assumption that under optimal nodal pricing passive transmission line owners collect all the congestion rents on a constrained line, as well as incremental loss

rents, is not supported by the experimental results in a three-node radial network system with four buyers and six generators at two dispersed locations.

2. Market efficiency results:
   (i) Efficiency is increased with more (twice) experienced subjects by only 0.6 percentage points, which is not statistically significant.
   (ii) Efficiency is reduced by a line constraint, and this is statistically significant.
   (iii) The other-side auction rule, giving temporary time priority to accepted bids and offers, increases efficiency (by 5.5 percentage points which is highly significant).
3. Profit share results for generators (G1) upstream from the line that is constrained under some treatments:
   (i) More experience reduces generator share of profits significantly (3.6 percentage points).
   (ii) The effect of the line constraint is to increase generator profit share (by 165 percentage points which is highly significant), as upstream generators raise their offers and capture much of the transmission share of the congestion rents.
   (iii) The other-side auction rule increases the G1 share of profits (by 4.9 percentage points which is significant).
4. Profit share of wholesale buyers:
   (i) Increased experience improves the profit share of buyers. This is because, as seen in Figure 2, seller surplus exceeds buyer surplus at the competitive equilibrium, and convergence is relatively slow from below as sellers learn over successive sessions to bargain more effectively in the auction.
   (ii) The line constraint has an infinitesimal effect on buyer profits.
   (iii) Buyer profits are increased 1.4 percentage points by the other-side rule, but this could be due to sampling error.
5. Profit share of generators (G2) served by the line which is never constrained:
   (i) Increased experience has no important effect on the G2 share.
   (ii) When the other line is constrained this increases G2 share of profit by 1 percentage point. Hence generators extract some of the incremental loss revenue of a transmission line, but we cannot rule out that this is due to sampling variation.
   (iii) The other-side rule increases the G2 share of profit (by 5.8 percentage points and this is significant).

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