PAY-AS-BID PRICING IN COMBINED POOL/BILATERAL ELECTRICITY MARKETS

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Abstract – In the context of combined pool/bilateral operation of electricity markets, this paper compares two pricing strategies: pay-as-bid and the more conventional marginal pricing. The pay-as-bid strategy defines three types of services: bilateral contract generation, transmission loss and congestion management required by the bilateral contracts, and pool demand generation including associated transmission loss and congestion. A technique is developed to unbundle these three services, thus identifying the corresponding costs and power levels from the points of view of both loads and generators. The unbundling process follows an approach that integrates the cost and generation components along a predefined load trajectory. The unbundled costs are useful economic signals for agents in their choice of a beneficial mix of pool/bilateral trading.

Keywords: marginal pricing, pay-as-bid, pool operation, bilateral contracts, cost unbundling, service unbundling, economic signals.

1 INTRODUCTION

In general, two pricing strategies can be used in the settlement of electricity markets. One is marginal pricing, in which the most expensive scheduled generator defines the system price. A second pricing approach, referred to as pay-as-bid, pays each generator the actual amount of its submitted bid.

Most electricity markets have adopted marginal pricing, with the exception of the new trading agreement rules in England & Wales that have moved from marginal pricing to a pay-as-bid scheme [1, 2]. Recent research indicates that the latter approach may be beneficial in overcoming some of the problems that arise in the current market operation, that is, to reduce price volatility and discourage the exercise of market power [3]. Support for the pay-as-bid method however is not uniform, as some argue that its application may lead to inefficiency and weaken competition [2, 4].

So far, research on pay-as-bid pricing has focused on generator bidding strategies [2, 3, 5]. We feel however that to develop informed bidding strategies, it is also necessary to analyze the financial implications of specific pay-as-bid market rules. In this paper we consider a pay-as-bid scheme based on the Auman-Shapley technique [8] and apply it to electricity markets that allow combined pool/bilateral contract operation [6]. This type of mixed electricity market is very general and can model a pure pool or a pure bilateral market, as well as mixtures of these.

Electricity markets generally trade various distinct services, each of which has to be priced in some rational and systematic manner. The services traded under the combined pool/bilateral electricity market being studied here are the supply of power to meet the pool and the bilateral demands, as well as any associated transmission loss and congestion management. The Auman-Shapley (AS) approach followed here offers features not present in simpler pay-as-bid schemes such as pro-rata. The AS approach accounts for losses and transmission congestion in a piece-wise incremental manner that uniquely unbundles the various services and allocates them among the market players.

This paper compares conventional marginal pricing with the proposed AS pay-as-bid approach in a combined pool/bilateral market. The two pricing methods are compared through costs, average prices, and revenues and through payments from the perspective of the generators, loads, and bilateral contract parties. The combined pool/bilateral market is settled by a system operator according to an AC optimal power flow that accounts for bilateral contracts, transmission loss and congestion management.

2 COMBINED POOL/BILATERAL OPERATION

The studies of the two pricing mechanisms for combined pool/bilateral dispatch examined in this paper are based on the mathematical formulation defined in [6] and summarized immediately below.

2.1 Pool and Bilateral Components of Generations and Loads

In combined pool/bilateral operation, both the generation and demand vectors, $\mathbf{P}_g$ and $\mathbf{P}_d$ respectively, are decomposed into bilateral and pool components,

$$\mathbf{P}_g = \mathbf{P}_g^p + \mathbf{P}_g^b = \mathbf{P}_g^p + \mathbf{GD}\cdot\mathbf{e} \qquad (1)$$

$$\mathbf{P}_d = \mathbf{P}_d^p + \mathbf{P}_d^b = \mathbf{P}_d^p + \mathbf{GD}^T\cdot\mathbf{e} \qquad (2)$$

The $(n\times n)$ matrix, $\mathbf{GD}$, describes the firm bilateral contracts between generators and loads. The element

GD_{ij} represents a firm agreement by which generator i is physically committed to produce this contracted power level. Similarly, load j is obliged to consume the same amount of power. For the sake of simplicity, it is assumed that each bus has only one load and/or one generator. In the above equations we have defined the n-dimensional vector $\mathbf{e}=[1\ \ldots 1]^T$.

The bilateral generation component, $\mathbf{P}_g^b$, supplies the bilateral portion of the demand, $\mathbf{P}_d^b$, so that total bilateral output of each generator has to match all of its bilateral agreements,

$$P_{gi}^b = \sum_{j=1}^{n} GD_{ij} \tag{3}$$

In a similar manner, the bilateral demand of each bus j is denoted by,

$$P_{dj}^b = \sum_{i=1}^{n} GD_{ij} \tag{4}$$

The pool generation component, $\mathbf{P}_g^p$, supplies both the pool demand, $\mathbf{P}_d^p$, as well as any transmission losses and congestion re-dispatch due to the combined effect of pool and bilateral demand.

2.2 Combined Pool/Bilateral Market Settlement

A generator i that wishes to participate in the spot market submits to the ISO its cost curve *bid/offer*, $C_i(P_{g_i})$ together with its MW bilateral commitments[1]. The total pool generation bid cost is then $C(\mathbf{P}_g) = \sum_{i=1}^{n} C_i(P_{g_i})$. These generation bids are submitted to supply not just the pool demand, but also the total system loss as well as any possible re-dispatch due to transmission congestion, in other words to participate in congestion management. The mixed pool/bilateral generation dispatch strategy followed by the ISO can then be expressed by the following optimal power flow problem,

$$\begin{aligned} &\underset{\mathbf{P}_g}{Min} \quad C(\mathbf{P}_g) \\ \text{s.t.} \quad &\mathbf{P}_g \in S \\ &\mathbf{P}_g \geq \mathbf{P}_g^b = \mathbf{GD}\cdot\mathbf{e} \end{aligned} \tag{5}$$

The set S above denotes the security region of the power system in the space of generation levels, $\mathbf{P}_g$. Such a region is defined by the range of the generator outputs, $\mathbf{P}_g^{\min} \leq \mathbf{P}_g \leq \mathbf{P}_g^{\max}$, by the load flow equations, $\mathbf{P}_g = \mathbf{P}_d + \mathbf{P}(\boldsymbol{\delta})$ [7], and by the transmission flow limits, $\left|\mathbf{P}_f(\boldsymbol{\delta})\right| \leq \mathbf{P}_f^{\max}$. The vector of voltage phase angles is denoted by $\boldsymbol{\delta}$, while the voltage magnitudes are assumed to be equal 1.p.u. at all buses.

[1] Under pay-as-bid generators bid above their true cost.

The solution of (5) yields the optimum levels of all the above-mentioned decision variables, including the generation vector, $\mathbf{P}_g^*$, as well as the nodal prices $\boldsymbol{\lambda}$ associated with the load flow equations.

The pool generation component can then be found by subtracting the scheduled bilateral generation from the total optimum generation, that is,

$$\mathbf{P}_g^p = \mathbf{P}_g^* - \mathbf{P}_g^b \tag{6}$$

The solution of (5) also defines the individual and total generation costs, respectively, $C_i(P_{gi}^*);\forall i$ and $C^* = \sum_i C_i(P_{gi}^*)$.

3 MARGINAL PRICING APPROACH

The following revisits various financial performance measures for generators and loads based on marginal pricing [6] and on the results from (5) and (6):

- Revenue of generator i from pool generation,

$$R_{gi}^p = \lambda_i \cdot P_{gi}^p \tag{7}$$

- Expenditure of load j for pool demand,

$$E_{dj}^p = \lambda_j \cdot P_{dj}^p \tag{8}$$

- Revenue of generator i from bilateral contracts,

$$R_{gi}^b = \sum_{j=1}^{n} \pi_{ij}^b GD_{ij} \tag{9}$$

- Expenditure of load j for its bilateral contracts,

$$E_{dj}^b = \sum_{i=1}^{n} \pi_{ij}^b GD_{ij} \tag{10}$$

The bilateral contract rates, π_{ij}^b, are confidential privately negotiated long-term agreements between the bilateral trading partners, generator i and load j. The negotiated prices may differ from the nodal prices and therefore lead to either a profit or a loss in comparison with the spot market price.

Under marginal pricing, the incremental cost of transferring power from bus i to bus j is equal to the difference in nodal prices, that is, $\lambda_j - \lambda_i$. This rate defines the amount charged by the pool to the bilateral exchange GD_{ij} for transmission loss and congestion management[2],

$$E_{ij}^{bcl} = (\lambda_j - \lambda_i)\, GD_{ij} \tag{11}$$

As E_{ij}^{bcl} is associated with a bilateral contract and not uniquely with either the selling generator i or with the buying load j, this payment can be split in arbitrary proportions between the two participants. In this paper,

[2] The superscript ‘bcl’ stands for bilateral-congestion-loss.

this proportion is set to 50/50 so that the power transfer payment assigned to generator i is $E_{ij}^{bcl}/2$, with the same amount charged to load *j*. Splits other than 50/50 can be negotiated but will affect the bilateral contract price. Irrespective of the split, a large power transfer payment for a specific contract acts as a disincentive and will discourage future agreements between these two partners.

Thus, the total power transfer expenditure of generator i for all its contracts is then,

$$E_{gi}^{bcl} = \frac{1}{2}\sum_{j=1}^{n}\left(\lambda_j - \lambda_i\right)GD_{ij} \tag{12}$$

Similarly, the total power transfer expenditure of load j for all its contracts is,

$$E_{dj}^{bcl} = \frac{1}{2}\sum_{i=1}^{n}\left(\lambda_j - \lambda_i\right)GD_{ij} \tag{13}$$

Finally, the net revenue of generator i is,

$$R_{gi} = R_{gi}^{p} + R_{gi}^{b} - E_{gi}^{bcl} \tag{14}$$

while the total expenditure of load *j* is,

$$E_{dj} = E_{dj}^{p} + E_{dj}^{b} + E_{dj}^{bcl} \tag{15}$$

The total flow of expenditures and revenues under marginal pricing in combined pool/bilateral markets can now be summarized. We begin with the total expenditures by the consumers,

$$\begin{aligned} E_d^{total} &= \sum_{j=1}^{n}E_{dj} = \sum_{j=1}^{n}E_{dj}^{p} + \sum_{j=1}^{n}E_{dj}^{b} + \sum_{j=1}^{n}E_{dj}^{bcl} \\ &= \sum_{j=1}^{n}\lambda_j P_{dj}^{p} + \sum_{i,j=1}^{n}\pi_{ij}^{b}GD_{ij} + \frac{1}{2}\sum_{i,j=1}^{n}\left(\lambda_j - \lambda_i\right)GD_{ij} \end{aligned} \tag{16}$$

Similarly, the total net revenues by the generators are,

$$\begin{aligned} R_g^{total} &= \sum_{i=1}^{n}R_{gi} = \sum_{i=1}^{n}R_{gi}^{p} + \sum_{i=1}^{n}R_{gi}^{b} - \sum_{i=1}^{n}E_{gi}^{bcl} \\ &= \sum_{i=1}^{n}\lambda_i P_{gi}^{p} + \sum_{i,j=1}^{n}\pi_{ij}^{b}GD_{ij} - \frac{1}{2}\sum_{i,j=1}^{n}\left(\lambda_j - \lambda_i\right)GD_{ij} \end{aligned} \tag{17}$$

Under marginal pricing, the difference between the total load expenditures and the total net generator revenues is in general a positive quantity. This surplus is referred to as the merchandising surplus, MS. These monies remain with the ISO and are intended to cover part of the network expenses including expansion. The merchandising surplus also acts as an economic signal to stimulate new additions to the network.

Marginal pricing does not guarantee positive generator profits, $R_{gi} - C_{gi}$, particularly if the generator has engaged in long-term bilateral agreements at insufficiently high rates, π_{ij}^{b}.

4 INTEGRATED MARGINAL PRICE PAY-AS-BID METHOD

4.1 Unbundled Services and Costs

Here we propose a pay-as-bid pricing method for combined pool/bilateral markets, where we distinguish three services provided by the generators and received by the consumers and by the bilateral contract parties.

From the point of view of generator $i; \forall i$, these distinct services are:

- P_{gi}^{pcl} = generation component that supplies the pool demand plus its share of loss and congestion management.
- P_{gi}^{bcl} = generation component that supplies a share of loss and congestion management allocated to all bilateral contracts[3].
- $P_{gi}^{b} = \sum_{j=1}^{n} GD_{ij}$ = generation component that supplies the bilateral agreements between generator i and all loads.

The total generation is the sum of these three services,

$$P_{gi} = P_{gi}^{pcl} + P_{gi}^{bcl} + P_{gi}^{b} = P_{gi}^{pcl} + P_{gi}^{bcl} + \sum_{j=1}^{n}GD_{ij} \tag{18}$$

while the total pool generation is $P_{gi}^{p} = P_{gi}^{pcl} + P_{gi}^{bcl}$.

In this method, as in equation (2), each load j submits two demand components to the pool, namely, the pool demand, P_{dj}^{p}, and the bilateral demand, $P_{dj}^{b} = \sum_{i=1}^{n} GD_{ij}$. The pool demand components, $P_{dj}^{p}; \forall j$, are supplied by the generation service, $P_{gi}^{pcl}; \forall i$, while the bilateral demand components, $P_{dj}^{b}; \forall j$, are supplied by the two generation services, $P_{gi}^{b}; \forall i$, which is priced by private agreements, and $P_{gi}^{bcl}; \forall i$, which is priced by the ISO.

The costs of the services provided by generator i are:

- C_{gi}^{pcl} = generation cost component for the supply of $P_{gi}^{pcl}; \forall i$.
- C_{gi}^{bcl} = generation cost component for the supply of $P_{gi}^{bcl}; \forall i$.

[3] Not just its own contracts. Thus, a generator with no bilateral contracts can still supply some P_{gi}^{bcl}.

- C_{gi}^{b} = generation cost component for the supply of $P_{gi}^{b} = \sum_{j=1}^{n} GD_{ij}$.

The total generation cost $C_i(P_{gi}^{*})$ is the sum of these three service costs,

$$C_i(P_{gi}^{*}) = C_{gi}^{pcl} + C_{gi}^{bcl} + C_{gi}^{b} \tag{19}$$

From the point of view of the loads, we define,

- C_{dj}^{p} = cost component allocated to load j for its pool demand, P_{dj}^{p} .

From the point of view of the bilateral contracts, we define,

- C_{ij}^{bcl} = cost component allocated to bilateral contract, GD_{ij} , for the supply of associated loss and congestion management.
- C_{ij}^{b} = cost component allocated to the bilateral contract between generator i and load j for the supply of GD_{ij} .
-

4.2 Reconciliation of Costs

Under the pay-as-bid scheme, the costs allocated to the loads and bilateral contracts must exactly match the generation cost components. Thus, for the supply of pool demand and associated loss and congestion management, we have,

$$\sum_{i=1}^{n} C_{gi}^{pcl} = \sum_{j=1}^{n} C_{dj}^{p} \tag{20}$$

Similarly, for the services received by the bilateral contracts, the financial balance equation for loss and congestion management is,

$$\sum_{i=1}^{n} C_{gi}^{bcl} = \sum_{i=1}^{n}\sum_{j=1}^{n} C_{ij}^{bcl} \tag{21}$$

Finally, the costs of supplying power to the bilateral contracts must satisfy,

$$\sum_{i=1}^{n} C_{gi}^{b} = \sum_{i=1}^{n}\sum_{j=1}^{n} C_{ij}^{b} \tag{22}$$

4.3 Calculation of Unbundled Generation and Cost Components

The cost and generation unbundling follows an integration process [7, 8] that modifies the two load components (bilateral and pool) in small increments, one at a time. The optimum generation dispatch (5) is solved for each intermediate value of the load components along a linear uniform integration path[4] from zero to their final specified values. This path is characterized by a scalar $t; 0 \le t \le 1$.

The integration process begins with all generation and cost variables set to zero. Each integration step has three parts that are now described.

<u>(1) Integration sub-step 1</u>:

- Increase only the bilateral contracts by $d\mathbf{GD}$, keeping $d\mathbf{P}_{d}^{p} = \mathbf{0}$.
- Solve (5) with new load levels for λ_i , for the incremental cost, IC_i , and for $dP_{gi}^{*}; \forall i$,
- Then,

$$dP_{gi}^{bcl} = dP_{gi}^{*} - \sum_{j=1}^{n} dGD_{ij} \tag{23}$$

- For each i and j , calculate:

$$dC_{gi}^{bcl} = \lambda_i \cdot dP_{gi}^{bcl} \tag{24}$$

$$dC_{ij}^{b} = IC_i \cdot dGD_{ij} \tag{25}$$

$$dC_{gi}^{b} = \sum_{j=1}^{n} dC_{ij}^{b} \tag{26}$$

$$dC_{dj}^{b} = \sum_{i=1}^{n} dC_{ij}^{b} \tag{27}$$

$$dC_{ij}^{bcl} = (\lambda_j - \lambda_i) \cdot dGD_{ij} \tag{28}$$

<u>(2) Integration sub-step 2</u>:

- Increase only the pool demand by $d\mathbf{P}_{d}^{p}$, while keeping the bilateral contracts constant,
- Solve (5) with new load levels for λ_i , IC_i and $dP_{gi}^{*}; \forall i$
- Then,

$$dP_{gi}^{pcl} = dP_{gi}^{*} \tag{29}$$

- For each i and j , calculate:
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$$dC_{gi}^{pcl} = \lambda_i \cdot dP_{gi}^{pcl} \tag{30}$$

$$dC_{dj}^{pcl} = \lambda_i \cdot dP_{dj}^{p} \tag{31}$$

<u>(3) Integration of incremental variables</u>:

The increments calculated above are added over a sufficiently large number of integration steps [7] until both the pool and the bilateral demands reach their final values. The final integrated values define the desired unbundled generation and cost components defined earlier. Thus, denoting dx as any of the above incre-

[4] Three possible integration paths could be defined: (a) integrate by increasing a pool demand first, then bilateral; (b) increase bilateral demand first, then pool; (c) increase both demands simultaneously. In this paper the third approach is applied, but within integration step a bilateral supply is increased first.

mental variables, its final integrated value is determined by,

$$x = \int_{t=0}^{1} dx(t) \tag{32}$$

4.4 Revenues and Expenditures

Under pay-as-bid pricing, the revenues of the generators and the payments of the loads and the bilateral contracts must match the corresponding unbundled costs. This is applicable only for those services managed by the system operator.

$$\begin{aligned} R_{gi}^{pcl} &= C_{gi}^{pcl} & \qquad R_{gi}^{bcl} &= C_{gi}^{bcl} \\ E_{dj}^{p} &= C_{dj}^{p} & \qquad E_{ij}^{bcl} &= C_{ij}^{bcl} \end{aligned} \tag{33}$$

On the other hand, the privately negotiated generator revenues and load expenditures for the bilateral contracts (excluding loss and congestion management) are not necessarily equal to the corresponding unbundled cost quantities,

$$R_{gi}^{b} = \sum_{j=1}^{n} \pi_{ij}^{b} GD_{ij} \neq C_{gi}^{b} \tag{34}$$

$$E_{dj}^{b} = \sum_{i=1}^{n} \pi_{ij}^{b} GD_{ij} \neq C_{dj}^{b} \tag{35}$$

As in marginal pricing, the payment E_{ij}^{bcl} is attributed to both contract parties, and can be divided between them in an arbitrary way. In this paper we have adopted a 50/50 split so that the payment of generator i for all its bilateral contracts is,

$$E_{gi}^{bcl} = \frac{1}{2}\sum_{j=1}^{n} E_{ij}^{bcl} \tag{36}$$

Similarly, the expenditure of load j becomes

$$E_{dj}^{bcl} = \frac{1}{2}\sum_{i=1}^{n} E_{ij}^{bcl} \tag{37}$$

Therefore, the net revenue of generator i is,

$$R_{gi} = R_{gi}^{pcl} + R_{gi}^{bcl} + R_{gi}^{b} - E_{gi}^{bcl} \tag{38}$$

Likewise, the total expenditure of load j is,

$$E_{dj} = E_{dj}^{pcl} + E_{dj}^{bcl} + E_{dj}^{b} \tag{39}$$

Figure 1 illustrates the monetary and information flows between the ISO and generations and loads, as well as between bilateral parties engaged in a trade. These flows are based on the previously derived cost, revenue and expenditure components.

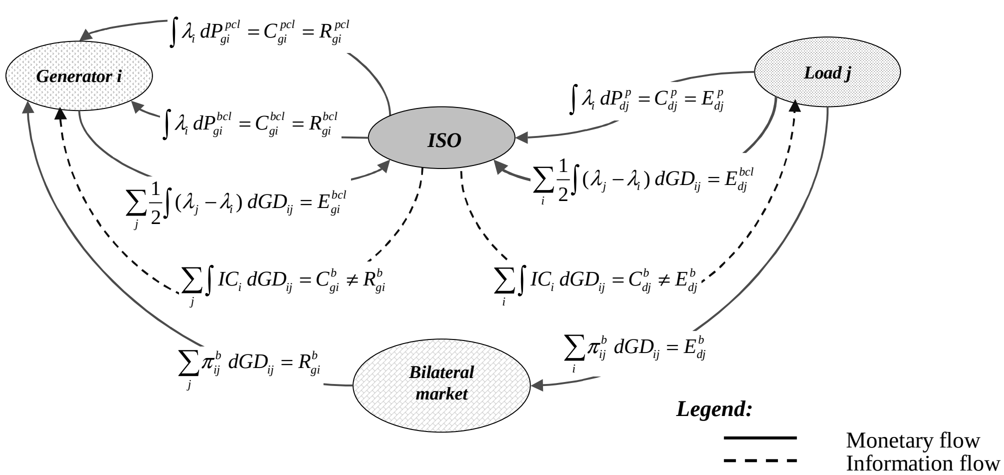

Figure 1:Implementation of Pay-As-Bid Method: Monetary and information flows

Under pay-as-bid, from (38) and (39), one can see that the sum of the consumer expenditures, $\sum_{j=1}^{n} E_{dj}$, is identical to the sum of the generator revenues, $\sum_{i=1}^{n} R_{gi}$, so that, in contrast with marginal pricing, the merchandising surplus (MS) is nil. It can be argued that having MS=0 is an advantage since it avoids having to distribute a non-zero MS among the various competing agents in an ad-hoc manner. Moreover, zero MS removes any financial interest on the part of the agents to increase the size of the surplus. Payments to the transmission provider for transmission use will be based on a regulated tariff. As will be seen in the simulation results, the absence of MS does not imply that bilateral contracts do not incur power transfer expenditures. In fact, each contract pays C_{ij}^{bcl} whose combined amount exactly covers the total cost of generating the "bilateral congestion loss" components, P_{gi}^{bcl} .

5 COMPARATIVE STUDIES

A 5-bus network [5] is used to evaluate the financial performance measures for the proposed pay-as-bid strategy, and to compare them with the marginal pricing method. In this example, the fixed generator costs are set to zero. When these are non-zero, they are allocated among the pool and bilateral components in a pro-rata manner.

The system demand of 1088 MW is distributed among the network buses according to,

$$\mathbf{P}_d^b + \mathbf{P}_d^p = [34 \;\; 85 \;\; 119 \;\; 323 \;\; 527]^T \quad MW \qquad (40)$$

The firm bilateral contracts are,

$$\mathbf{GD} = \begin{bmatrix} 33.4 & 50.1 & 33.4 & 150.3 & 167 \\ 0 & 33.4 & 33.4 & 116.9 & 250.5 \\ 0 & 0 & 50.1 & 50.1 & 100.2 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \end{bmatrix} \quad MW \qquad (41)$$

Thus, the total system load is divided among the bilateral and pool markets in the proportion of 98% (1068.8 MW) for bilateral contracts and 2% (19.2 MW) for pool demand. After solving the minimum cost dispatch (5), this pattern of pool and bilateral demand causes generator 1 to operate out of merit and congests line 1-4.

In this simulation, the bilateral tariffs were chosen by,

$$\pi_{ij}^b = \frac{dC_i}{dP_{g_i}}(P_{g_i}^b) \;\; \forall\, j \qquad (42)$$

Table 1 summarizes the results of the unbundling process for 1000 integration steps. The integration path followed increases both bilateral and pool demands simultaneously and uniformly across all nodes. Table 1 shows the bus optimal generation and load components, the nodal prices, the bilateral tariffs, and the optimal generation costs. Under marginal pricing, only the total pool generation component, $\mathbf{P}_g^p$, is determined and used for financial calculations. However, the pay-as-bid approach decomposes it further into "only pool supply", $\mathbf{P}_g^{pcl}$, and the bilateral services component, $\mathbf{P}_g^{bcl}$.
Further results comparing the marginal pricing and integrated "pay-as-bid" methods are shown in Tables 2 and 3, respectively. Examining the total revenues and expenditures reveals that both generators and loads are better off under the integration pay-as-bid mechanism compared to marginal pricing, primarily due to the absence of merchandising surplus. Nevertheless, generators are still responsible for half of the power transfer payments for their bilateral contracts. Under pay-as-bid the total of such power transfer payments is 767 $/h versus 2473 $/h under marginal pricing. This difference that applies equally for both generators and loads is particularly significant under congestion. From the point of view of pool generation, however, we see from Tables 2 and 3 that the general tendency is for generators to earn less under pay-as-bid.

	Bus 1	**Bus 2**	**Bus 3**	**Bus 4**	**Bus 5**	**Sum**
P_g^b	434.2	434.2	200.4	0	0	1,068.8
P_g^{bcl}	-4.1	1.9	50.6	0	0	48.4
P_g^{pcl}	4.1	12.2	3.7	0	0	20
P_g^p	0	14.2	54.2	0	0	68.3
P_g	434.2	448.4	254.6	0	0	1,137.1
* P_d^b	33.4	83.5	116.9	317.3	517.3	1,068.8
* P_d^p	0.6	1.5	2.1	5.7	9.3	19.2
* P_d	34	85	119	323	527	1,088
λ	32.5	34.4	36.5	37.8	40.8	-
* π_g^b	37.4	34	34	56	57	-
C_g	12,455	12,431	7,823	0	0	32,708

Table 1: Summary of unbundled generation services. Power in MW, λ and π_g^b in $/MWh, and C_g in $/h. The rows marked with an asterisk contain given data. All other values are calculated by the optimization.

	Bus 1	**Bus 2**	**Bus 3**	**Bus 4**	**Bus 5**	**Sum**
R_g^b	16,225	14,774	6,817	0	0	37,816
R_g^p	0	488	1,975	0	0	2,463
E_g^{bcl}	1,198	1,024	251	0	0	2,473
R_g	15,027	14,238	8,541	0	0	37,807
E_d^b	1,248	3,009	4,089	11,298	18,173	37,816
E_d^{bcl}	0	48	99	619	1,707	2,473
E_d^p	19.5	51.7	76.6	215.2	379.6	742.6
E_d	2,465	4,084	4,416	11,514	18,552	41,032

Table 2: Marginal pricing approach; revenues and expenditures are in $/h.

We can also see from Tables 1 and 3 that there can exist some negative generation and cost components. This is due to the presence of excessively high bilateral generation levels that force generators to operate out of merit. For example, generator 1 has negative revenue of -100.3 $/h for its " bilateral loss congestion" component. This is an effective financial "signal" indicating that its choice of bilateral contracts is inefficient.

	Bus 1	**Bus 2**	**Bus 3**	**Bus 4**	**Bus 5**	**Sum**
$R_g^b \neq C_g^b$	16,225	14,774	6,817	0	0	37,816
$R_g^{bcl} = C_g^{bcl}$	-100.3	-65.1	1,697.8	0	0	1,532.4
$R_g^{pcl} = C_g^{pcl}$	90.3	352	121.7	0	0	564
$R_g^p = C_g^p$	-10	286.9	1,819.5	0	0	2,096.4
E_g^{bcl}	324.7	358.4	84	0	0	767
R_g	15,891	14,703	8,553	0	0	39,147
E_d^b	1,248	3,009	4,089	11,298	18,173	37,816
E_d^{bcl}	0	5.6	28.7	159.7	573.1	767
E_d^p	16.6	41.8	60.1	164.8	280.6	564
E_d	1,265	3,056	4,178	11,623	19,026	39,147

Table 3: Integrated pay-as-bid approach; revenues and expenditures in \$/h.

Another important by-product of the integration unbundling method, are the cost components C_{gi}^b and C_{dj}^b. For example, generator i would consider its bilateral contracts profitable if its net bilateral contract revenue exceeds its allocated bilateral cost,

$$R_{gi}^b - E_{gi}^{bcl} > C_{gi}^b \tag{43}$$

Similarly, load j would be satisfied with its negotiated bilateral contracts if its total bilateral contract payment is less than its allocated bilateral cost,

$$E_{dj}^b + E_{dj}^{bcl} < C_{dj}^b \tag{44}$$

Referring to Table 4, this simulation shows that all three generators have beneficial bilateral deals. In contrast the loads are all paying more in bilateral services than their allocated costs. In future negotiations, the loads may opt to buy more from the pool or renegotiate their bilateral deals. As can be seen from the last two rows of Table 4, the average prices paid by the loads for pool demand are considerably lower than the average prices paid for bilateral demand.

	Bus 1	**Bus 2**	**Bus 3**	**Bus 4**	**Bus 5**	**Sum**
C_g^b	12,468	12,147	6,005	0	0	30,621
$R_g^b - E_g^{bcl}$	15,901	14,416	6,733	0	0	38,584
C_d^b	959	2,373	3,395	9,088	14,806	30,621
$E_d^b + E_d^{bcl}$	1,248	3,014	4,117	11,458	18,746	37,049
$(E_d^b + E_d^{bcl}) / P_d^b$	37.4	36.1	35.2	36.1	36.2	-
E_d^p / P_d^p	27.7	27.9	28.6	28.9	30.2	-

Table 4: Comparison of allocated bilateral costs and net bilateral revenues and expenditures (\$/h). Average bilateral and pool load prices (\$/MWh).

In the previous analysis the method was illustrated on a 5-bus system. To reduce the computational time in realistic-sized networks, it is possible to first calculate unbundled costs for a smaller number of integration steps, and then normalize the approximate generator costs and load payments to ensure that their sums equal their exact final values. Table 5 illustrates the effect of the number of steps on the integration process for a modified IEEE 24 bus system. The estimated unbundled costs given in rows 4-7 are normalized as indicated above, and reveal that even with a reduced number of steps sufficient unbundling accuracy is obtained.

	Number of Integration Steps				
	10	100	1000	2000	4000
C	40,302	40,302	40,302	40,302	40,302
C_g	39,962	40,268	40,299	40,301	40,302
$C_{.d}$	39,951	40,270	40,299	40,301	40,302
$\hat{C}_g^{pcl} = \hat{C}_d^{pcl}$	33,399	33,103	33,074	33,072	33,071
$\hat{C}_g^b = \hat{C}_d^b$	6,941	7,232	7,261	7,262	7,263
$\hat{C}_g^{bcl} = \hat{C}_d^{bcl}$	-17	-9	-8	-8	-8
$\hat{C}_g^{wcl} = \hat{C}_d^{wcl}$	-22	-24	-24	-24	-24

Table 5: Unbundled costs vs. number of integration steps for modified IEEE 24bus system with 83% of pool and 17% bilateral supply, as well as a wheeling contract between buses 3 and 20.

6 CONCLUSIONS

In the context of combined pool/bilateral operation of electricity markets, this paper compares two pricing strategies: pay-as-bid and the more conventional marginal pricing. The pay-as-bid strategy defines three types of services: bilateral contract generation, transmission loss and congestion management required by the bilateral contracts, and pool demand generation including associated transmission loss and congestion. A technique is developed to unbundle these three services, thus identifying the corresponding costs and power levels from the points of view of both loads and generators. The unbundling process follows an approach that integrates the cost and generation components along a predefined load trajectory. The results suggest that under transmission congestion the pay-as-bid approach is beneficial for both loads and generators due to the absence of a merchandising surplus. As a result, the power transfer payments are considerably reduced for both generators and loads. The specific simulation test case clearly indicates that the average price for pool demand is lower than the average price for bilateral demand. The unbundled costs are therefore useful economic signals for agents in their choice of a beneficial mix of pool/bilateral trading. In this example, the loads would either renegotiate their bilateral deals or switch to a greater proportion of pool demand.

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