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联营电力市场中需求侧的直接参与

Chua-Liang Su，Daniel Kirschen

（曼彻斯特大学 电气与电子工程学院，英国 曼彻斯特）

Direct Participation of Demand-Side in a Pool-Based Electricity Market

Chua-Liang Su，Daniel Kirschen

（School of Electrical and Electronic Engineering，The University of Manchester，Manchester，UK）

ABSTRACT: In existing day-ahead pool markets that allow demand-side bidding, bids for MW purchase are rejected whenever the market clearing prices at the periods concerned are greater than the bid prices. As the consumer is not in the business to make profits through curtailing energy, the unsatisfied demand has to be acquired through balancing market, at periods closer to intended consumption. This exposes the consumer to greater risk of not meeting its energy requirement at a desirable cost. A novel market concept is introduced by allowing demand-side bidders to reduce the risk of going unbalanced after the gate closure of day-ahead market. This is done by incorporating a demand shifting mechanism within auction rules.

KEY WORDS: market clearing tool；maximum social welfare；demand side participation；demand shifting；pool-based electricity market；perfect competition；mixed-integer LP

摘要：在现有的允许需求侧竞标的日前联营市场中，每当某个时段的市场清算电价高于投标报价时，需求侧的兆瓦级购电竞标就被拒绝。由于用户不参与通过削减供电量来牟利的商业运作，因此未得到满足的用户需求只能从平衡市场中在更接近于预期用电的时段中获得。这就使用户遭受更大的不能以所希望的价格来满足其对电能的需要的风险。文章介绍了一种新的市场概念，它能在日前市场对需求侧的竞标者关闭后，以合并拍卖规则中需求移动机制的方法来降低其需求不平衡的风险。

关键词：市场清算工具；最大社会福利；允许需求侧参与；需求移动；基于联营的电力市场；完全竞争；混合整数线性规划

0　INTRODUCTION

Constants. Δt:duration of time interval; s_G^i incremental production cost of generating unit I; K^i: fixed cost bid of generating unit I; p : price of electricity; p_H :electricity price below which the demand becomes price responsive; p_L : electricity price at which the total of price responsive and price taking demand is equal to the forecasted demand; $\underline{D}^{k,t}$: minimum amount of MW that can be consumed by bidder k at period t; $\overline{D}^{k,t}$: maximum amount of MW that can be consumed by bidder k at period t; $D_E^{k,j}$: demand consumption at elbow point j of price responsive bidder k; D_F^t : forecasted day-ahead system load at period t; $D_S^{k,t}$: fixed amount of demand requested by bidder k at period t of a “price-volume” bid; $D_T^{z,t}$: amount of demand requested by price taking bidder z at period t; $\overline{E}^k$: maximum amount of energy that is required by the price responsive bidder k; IO^i : length of time the unit is online (positive sign) or offline (negative sign) initially; LPF : fraction of system load being price responsive; $MB_{Sg}^{k,j,t}$: marginal benefit of consuming electricity at segment j of price responsive bidder k during period t; N_G^i : no load cost of generating unit I; $\underline{P}^i$: minimum stable generation of unit i; $\overline{P}^i$: maximum capacity of generating unit i; $P_E^{i,j}$: output level of generating unit i at elbow point j; Q : amount of energy purchased; Q_F : amount of forecasted energy demand in day-ahead market; Q_{RE} : fraction of Q_F that is price responsive to electricity price; Q_T : fraction of Q_F that is perfectly inelastic.

Variables. e : elasticity of demand; $\bar{p}$: generic weighted average variable; $\bar{p}_D$: weighted average electricity cost of system demand; $\bar{p}_G$: weighted average operation cost of generators; $\bar{p}_P$: weighted average electricity price received by generators; $\bar{p}_R$: weighted average electricity cost of price responsive demand; $\bar{p}_T$: weighted average electricity cost of price taking demand; $\bar{\bar{p}}$: relative saving in cost or loss of revenue; $\bar{\bar{p}}_{\mathrm{D}}$: relative saving in electricity cost of the system demand; $\bar{\bar{p}}_{\mathrm{G}}$: relative saving in operation cost of the generators; $\bar{\bar{p}}_{\mathrm{P}}$: relative loss in revenue of the generators; $\bar{\bar{p}}_{\mathrm{R}}$: relative saving in electricity cost of the shifting price responsive bidder; $\bar{\bar{p}}_{\mathrm{T}}$: relative saving in electricity cost of the price taking bidder.

Variables (cont). $\bar{\bar{p}}_{\mathrm{TA}}$: relative benefit obtained by all the participant groups; $\bar{\bar{p}}_{\mathrm{TD}}$: relative benefit obtained by all the demand-side; $\bar{\bar{p}}_{\mathrm{TG}}$: relative benefit obtained by all the supply-side; CGS^t : consumers' gross surplus, \$/h. ; $D^{k,t}$: power consumedby demand-side bidder k at period t; $D_{\mathrm{Sg}}^{k,j,t}$: demandconsumption at segment j of demand-side bidder k during period t; MCP^t : market clearing price at period t; $P^{i,t}$: actual generation in MW of unit i at period t; $P_{\mathrm{Sg}}^{i,j,t}$: output level of generating unit i atsegment j during period t; $SU^{i,t}$: start-up cost for generating unit i at period t; SOC^t : system operating cost; $u_{\mathrm{D}}^{k,t}$: bid status of price responsive bidder k at period t (0: accepted, 1: rejected); $u_{\mathrm{G}}^{i,t}$: status of generating unit i at period t (0: on, 1: off); X^t : data elements used in defining the weighted average variable; Y^t : parameters that provide weights to the data elements.

It has been widely recognised that consumers could adjust their demand in response to time-varying prices [1-3]. However, most market designs did not consider the fact that consumers might want to make up for the fact that they reduced or increased their demand in response to variations in prices. In the long run, demand-side bidders in electricity markets are likely to be roughly energy neutral. This means that consumers merely shift some of their demand from one period to another in response to price signals. If consumers reduced their demand during periods of high prices, and did not catch up at other times, this would mean that the value they put on electrical energy is not consistent. Market designs that do not recognise this energy neutrality characteristic is usually unsustainable. As an example, the now defunct Electricity Pool of England and Wales (EPEW) allowed participation of a limited number of consumers by treating a bid for a reduction in demand in a similar way to an offer for generation [4]. However this bidding mechanism is not as competitive as it seems due to the load recovery effect that invariably accompanies load reductions. As a result, it suffers from over-pricing of demand reduction resources [5]. The market clearing tool introduced in this paper does not suffer from this pricing inconsistency as bidders are charged for what they consume, rather than for how much they reduce demand.

In conventional day-ahead pool markets, demand-side bids are rejected if their values are lower than the market clearing prices. This bidding mechanism exposes the consumers to large amount of unsatisfied MW if the bid is rejected, which in turn has to be procured from balancing markets (5 minutes to 1 hour ahead) where prices can be rather erratic. If the consumer is flexible with the time periods of consumption, it would be useful if market rules allow the bidder to purchase MW in any periods on the scheduling day, as long as the market clearing price is higher than the bidding price.

For the sake of explaining the proposed auction mechanism, consider a simple 3-period auction as an example: Assume that a bidder requires 60 MWh of energy. This bidder values energy consumption at 40 \$/MWh and has an hourly consumption limit of 37 MW. Assume that the market clearing prices during these three periods are totally unpredictable. As such, the bidder submits three equal-size hourly "price-volume" bids of 20 MW (since it requires 60 MWh) at a price of 40 \$/MWh at each period, with the intention of minimising the risk of not fulfilling its entire energy requirement. If the market clearing prices turn out to be as shown in Tab.1, the demand bid at period 2 will be rejected.

Tab. 1 Conventional "price-volume" bidding rule

Period	Market clearing price	Allocated MW
1	25	20
2	50	0
3	35	20
Unsatisfied demand		20

As a result, the bidder is 20 MWh away from meeting its energy requirement. A novel bidding concept is introduced by allowing demand-side bidders the opportunity to reduce their overall energy cost while ensuring that they get the amount of energy they need. To illustrate this concept, the same bidder described previously is used in the next example. It can be observed in Table 1 that the rejected bid at period 2 cannot be "shifted" to period 1 or 3, even if the shift would improve the welfare of the bidder. The results in Tab.2 summarised the proposed market rule which

Tab. 2 Proposed “demand-shifting” bidding rule

Period	Market clearing price	Allocated MW
1	25	37
2	50	0
3	35	23
Unsatisfied demand		0

allows “shifting” of unsatisfied demand to other periods.

For simplicity, it is assumed in this example that the demand shifting does not affect the market clearing prices. With the proposed rule, the bidder is able to meet its entire energy requirement, as seen in Table 2. It can also be observed that a lager portion of its demand is allocated to the lowest price period (at period 1) as this would improve the system cost of serving demand (and hence the social welfare). However, not all of the previously “unsatisfied” demand is allocated to this period as the hourly consumption limit of the bidder is 37 MW. Hence, the proposed market clearing tool is able to a) recognise both the hourly and daily consumption limits of demand-side bidders, while b) managing the risk of these bidders of not meeting their total energy requirement on the scheduling day. The c) effective cost of submitting such a demand-shifting bid outperforms conventional “price-volume” bid for MW in most cases and lastly, the tool is c) flexible enough for participation of conventional consumers and generators.

While a majority of existing market structures are more akin to oligopoly than perfect competition, it can be expected that market power is less likely to occur if demand has high price elasticity [6-7]. As the proposed market clearing tool incorporates active demand biddings, a perfect competitive model is used as the market structure of the tool. Borghetti et al. developed an auction algorithm that implicitly allows demand shifting [8]. However, there are designated periods where the consumers may undertake load reduction or recovery and this unnecessarily complicates the market rules. As the consumers in the model do not contractually own the load reduction “resources”, the auction model is most likely to suffer from gaming opportunities. This is because the bidders could have claimed to perform load reduction when they actually have no intention to use electricity. Arroyo and Conejo presented an alternative market clearing tool for achieving maximum social welfare in a pool market [9]. The consumers in this auction model are required to submit bids to purchase MW explicitly. This means that the consumers will contractually own the demand if the bids are accepted. As such, the auction model does not suffer from the gaming problem associated with Borghetti et al.’s model. Nevertheless, the concept of demand shifting introduced by Borghetti et al. sparks the motivation to create a practical auction tool without the associated gaming problems. The proposed tool provides demand side participants a new bidding mechanism that is likely to reduce their overall energy cost (by shifting to periods with lower prices) while ensuring that they get the amount of energy they need. Furthermore, this bidding mechanism improves the economic efficiency of a market as demand shifting tends to flatten system load profile.

The remainder of this paper is organised as follows. In Section III, the problem of demand-supply matching is formulated. In addition, this section includes the modelling of the bidding behaviour of consumers and the method of quantifying the impact of demand-shifting on market participants. In Section 2, results from case studies are provided and discussed. Finally, some relevant conclusions are drawn in Section V.

1 PROBLEM STATEMENT AND FORMULATION

This section is mainly concerned with modelling the demand-supply matching problem of a pool electricity market. The goal of the problem is to maximise the social welfare of all market participants (i.e. demand-side consumers and supply-side generators). The market operator (MO) determines the optimal production and consumption schedules based on the bidding files submitted by the participants. In the proposed auction procedure, the market participants are allowed to include a set of parameters that define their complex operating characteristics, such as upward sloping power production cost and intertemporal constraints. The inclusion of these characteristics transforms the auction procedure into a unit commitment (UC) problem, in which there are strong dependencies between decisions in successive hours. The transmission network is taken to be sufficiently large that the network is never congested under any condition. Ancillary service such as spinning reserve is assumed to be traded in a separate market. If the production and the consumption of the market participants deviate from the amount allocated through the day-ahead auction, the difference is settled in the balancing market, which is assumed independent of the day-ahead auction. The planning horizon (T) of the auction is partitioned into 24 equally sized intervals with duration of 1 hour ($\Delta t = 1$).

1.1 Objective Function

The objective is to maximise the social welfare of all market participants and can be formulated as:

$$\max \sum_{t=1}^{T} (CGS^t - SOC^t) \tag{1}$$

In this equation and the rest of the paper, the following indices have been used unless specified otherwise: $i = 1,..,N$ for generating units;$j = 1,..,S_{\mathrm{G}}$ for segment/elbow points of cost curve;$j = 1,..,S_{\mathrm{D}}$ for segment of marginal consumption benefit; $k = 1,..,M$ for price responsive demand bidders; $t = 1,..,T$ for time periods of the optimization horizon; $z = 1,..,V$ for price taking demand bidders.

We will look at how complex offers for generation and bids for demand are modelled in the following two sub-sections. It is worth noting that if the generators or the consumers do not bid at their respective marginal benefits or costs, the objective function is not, strictly speaking, the social welfare but the ‘perceived’ social welfare. Nevertheless, a perfect competition model is adopted in this paper which assumes that all participants bid at their true benefits or costs.

1.2 Generators’ Offers

The design of generators’ offer files is based on EPEW’s complex bid structure. This bidding structure allows generators to submit multipart bids that represent two of their main characteristics: operation cost and operational constraints. The operation cost comprises the no load cost, the running cost and the start-up cost and can be given as

$$SOC^t = \sum_{i=1}^{N} (u_{\mathrm{G}}^{i,t} N_{\mathrm{G}}^{i} + \sum_{j=1}^{S_{\mathrm{G}}} s_{\mathrm{G}}^{i,j} P_{\mathrm{Sg}}^{i,j,t} + SU^{i,t}) \tag{2}$$

However, for the sake of simplicity, the start-up costs are considered constant for each unit, which can be given as

$$\begin{cases} SU^{i,t} - K^i (u_{\mathrm{G}}^{i,t} - u_{\mathrm{G}}^{i,t-1}) = 0 \\ SU^{i,t} \geq 0 \end{cases} \tag{3}$$

The following constraints place the output of each generator on one and only one segment of its piecewise linear cost curve and ensures that the total output of the generator is the sum of the production on each segment.

$$\begin{cases} P^{i,t} - \sum_{i=1}^{S_{\mathrm{G}}} P_{\mathrm{Sg}}^{i,j,t} = 0 \\ u_{\mathrm{G}}^{i,t} \underline{P}^{i} - P_{\mathrm{Sg}}{}^{i,1,t} \leq 0 \\ P_{\mathrm{E}}^{i,0} = 0 \\ 0 \leq P_{\mathrm{Sg}}{}^{i,j,t} \leq u_{\mathrm{G}}^{i,t} (P_{\mathrm{E}}^{i,j} - P_{\mathrm{E}}^{i,j-1}) \\ u_{\mathrm{G}}^{i,t} \underline{P}^{i} \leq P^{i,t} \leq u_{\mathrm{G}}^{i,t} \overline{P}^{i} \end{cases} \tag{4}$$

Generator’s ramp up and down rates [10] and minimum up and down time constraints [11] are omitted from the demand-supply matching problem to allow easier understanding of simulation results. The impact of the consideration of these constraints on the market can be found in [12].

1.3 Demand-Side Bids

Fig. 1 illustrates the assumption of the two categories of demand in the auction framework. They are the price taking demand and the price responsive demand respectively. As it is unrealistic to expect all system load to be price responsive, a fraction of the system load is modelled as perfectly inelastic (i.e. does not react to price at all). Although represented as infinitely large in the figure, the benefits of the price taking part are taken to be zero in the model due to computational reason: If the benefit is taken as infinity, it will inflate the value of social welfare artificially. On the other hand, taking them at an arbitrary constant value that is sufficiently large does not affect the outcome of the welfare maximisation process.

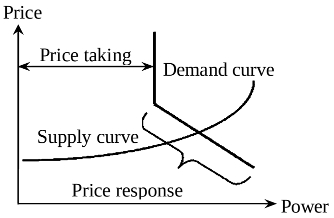

Fig. 1 Price taking and price responsive demand

The auction model allows demand to purchase a certain amount of energy ($D_{\mathrm{T}}^{z,t}$) regardless of the market clearing prices. This bid for demand is thus price-independent and the bidder will receive a schedule of deliveries equal to the specified volume for all hours of the scheduling horizon. On the other hand, the price responsive bid allows consumers to submit bids for MW that are sensitive to electricity prices. It is modelled in a way suitable for the participation of consumers which have means to rescheduling consumption (usually by utilising storage devices [12]) and is also flexible enough to allow for a conventional “price-volume” bid at a specific period. The bidder that submits a price responsive bid is also allowed to place a price taking bid (e.g. for meeting its inflexible demand) and vice versa. Similar to generators' offer files, the consumers' bid files are multipart and represent the two important characteristics of consumers: benefit of consuming demand (5) and consumption limits (6) to (8).

$$CGS^t = \sum_{k=1}^{M} \sum_{j=1}^{S_{\mathrm{D}}} MB_{\mathrm{Sg}}^{k,j,t} D_{\mathrm{Sg}}^{k,j,t} \tag{5}$$

$$\begin{cases} D^{k,t} - \sum_{j=1}^{S_{\mathrm{D}}} D_{\mathrm{Sg}}^{k,j,t} = 0 \\ u_{\mathrm{D}}^{k.t} \underline{D}^{k} - {D_{\mathrm{Sg}}}^{k,1,t} \le 0 \\ D_{\mathrm{E}}^{k,0} = 0 \\ 0 \le {D_{\mathrm{Sg}}}^{k,j,t} \le u_{\mathrm{D}}^{k.t} (D_{\mathrm{E}}^{k,j} - D_{\mathrm{E}}^{k,j-1}) \end{cases} \tag{6}$$

$$u_{\mathrm{D}}^{k,t} \underline{D}^{k} \le D^{k,t} \le u_{\mathrm{D}}^{k,t} \overline{D}^{k} \tag{7}$$

$$0 \le \sum_{t=1}^{T} D^{k,t} \Delta t \le \overline{E}^{k} \tag{8}$$

In an ideal world, the consumer will want to submit the lowest possible bidding prices and still meet its entire energy requirement. However, there is a certain price below which no generators are willing to produce. Therefore, the energy requirement (8) has to be modelled as an inequality constraint to ensure market clearance. The modelling of both the hourly consumption limits (7) and the daily energy requirement (8) effectively allows the consumer to perform demand shifting.

1.4 System Constraints

The UC schedule should provide the exact amount of power to meet the consumers' demand. Hence

$$\sum_{i=1}^{N} P^{i,t} - \sum_{k=1}^{M} D^{k,t} - \sum_{z=1}^{V} D_{\mathrm{T}}^{z,t} = 0 \tag{9}$$

1.5 Modelling of Bidding Behaviour

As the proposed market model is nonexistent, assumption has to be made on the part of consumers' bidding behaviour. The modelling of the bidding behaviour relies on the concept of price elasticity of demand [13]. Assume that the system demand at a particular period of the scheduling day is determined by the forecast as Q_{F}. If a fraction of Q_{F} is responsive to the electricity price (Q_{RE}), while the remaining is perfectly inelastic (Q_{T}), then Q_{F} can be given as

$$Q_{\mathrm{F}} = Q_{\mathrm{RE}} + Q_{\mathrm{T}} \tag{10}$$

The price elasticity of demand (e) provides a quantitative measurement of the sensitivity of demand to changes in electricity prices.

$$e = (p/Q) \cdot (\Delta Q / \Delta p) \tag{11}$$

Assume that Q_{RE} is linearly and inversely proportional to electricity price. Then, the priceelasticity of Q_{RE} can be represented as

$$e = -(p_{\mathrm{L}} / Q_{\mathrm{F}}) \cdot (Q_{\mathrm{F}} - Q_{\mathrm{T}}) / (p_{\mathrm{H}} - p_{\mathrm{L}}) \tag{12}$$

Let the fraction of forecasted system load being price responsive (LPF) be represented as

$$LPF = Q_{\mathrm{RE}} / Q_{\mathrm{F}} \tag{13}$$

Then, substituting (10) and (13) into (12) gives

$$e = -LPF \cdot p_{\mathrm{L}} / (p_{\mathrm{H}} - p_{\mathrm{L}}) \tag{14}$$

Hence, we can model an increased elasticity by increasing LPF.

It is assumed in this paper that the price responsive demand is always consistent with the value it places on consuming demand (i.e. price parameters p_{L} and p_{H} are constant and time invariant) throughout the scheduling horizon. LPF is also assumed to be time invariant for simplicity.

1.6 Quantifying the Impact of Demand Shifting

A weighted average method has been formulated to measure the impact of significant demand shifting on wholesale market participants quantitatively. Suppose the total purchase cost of the demand shifting price responsive bidder can be expressed as $\sum_{t=1}^{T} MCP^t D^{1,t}$. The weighted average cost per 1 MWh of energy to the demand shifting bidder ($\bar{p}_{\mathrm{R}}$) can then be given as

$$\bar{p}_{\mathrm{R}} = \sum_{t=1}^{T} MCP^t D^{1,t} \left(\sum_{t=1}^{T} D^{1,t} \right)^{-1} \tag{15}$$

The average of MCP (i.e. $\frac{1}{T} \sum_{t=1}^{T} MCP^t$) does not represent the consumption cost of the demand shifting bidder adequately as the bidder's consumption pattern is likely to vary in different periods. Therefore, it is more useful to utilise $\bar{p}_{\mathrm{R}}$ rather than the average of MCP to indicate the effective cost to the demand shifting bidder to consume 1 MWh as $\bar{p}_{\mathrm{R}}$ puts more weight on MCP^t at periods where consumption $D^{1,t}$ is higher. We can apply the weighted average concept introduced in to find the effective consumption or production cost of 1 MWh for all the other participant groups. Before we delve into that, let us express weighted average ($\bar{p}$) as the generic equation below

$$\bar{p}=\sum_{t=1}^{T}X^{t}Y^{t}(\sum_{t=1}^{T}Y^{t})^{-1} \tag{16}$$

Wher $$X^{t}\in\left\{MCP^{t},\sum_{i=1}^{N}\left(s_{\mathrm{G}}^{i,t}+\frac{u_{\mathrm{G}}^{i,t}N_{\mathrm{G}}^{i}+SU^{i,t}}{P^{i,t}}\right)\right\} \tag{17}$$

$$Y^{t}\in\left\{D_{T}^{1,t},D^{1,t},\sum_{i=1}^{N}P^{i,t}\right\} \tag{18}$$

We can then define the following weighted average variables according to different set members of X^{t} and Y^{t} as shown Tab. 3.

Tab. 3 Weighted average variables

Weighted average $\bar{p}$	Economic elements X^{t}	Weights Y^{t}
$\bar{p}v_{\mathrm{R}}$	MCP^{t}	$D^{1,t}$
$\bar{p}_{\mathrm{T}}$	MCP^{t}	$D_{\mathrm{T}}^{1,t}$
$\bar{p}_{\mathrm{D}}$	MCP^{t}	$D^{1,t}+D_{\mathrm{T}}^{1,t}$
$\bar{p}_{\mathrm{P}}$	MCP^{t}	$\sum_{i=1}^{N}P^{i,t}$
$\bar{p}_{\mathrm{G}}$	$\sum_{i=1}^{N}\left(s_{\mathrm{G}}^{i,t}+\frac{u_{\mathrm{G}}^{i,t}N_{\mathrm{G}}^{i}+SU^{i,t}}{P^{i,t}}\right)$	$\sum_{i=1}^{N}P^{i,t}$

As such, $\bar{p}$ of (16) can be defined by one of the set member below

$$\bar{p}\in\{\bar{p}_{\mathrm{R}},\bar{p}_{\mathrm{T}},\bar{p}_{\mathrm{D}},\bar{p}_{\mathrm{P}},\bar{p}_{\mathrm{G}}\} \tag{19}$$

In summary, the weighted average variable $\bar{p}$ represents the “normalised” effective cost or revenue of 1 MWh of the three participant groups, i.e. price taking bidder, price responsive bidder and generators. As such, we can evaluate the impact of demand shifting on these groups on a comparable basis. As we will observe in the numerical studies later, direct comparison of $\bar{p}$ in different market conditions can be made as a result of utilising this weighted average technique.

The demand shifting bidder should submit a price taking bid if $\bar{p}_{\mathrm{R}}$ is higher than $\bar{p}_{\mathrm{T}}$. Therefore, we need to compare the benefit obtained by the bidder to perform demand shifting, with respect to the case without demand shifting. The relative saving of the shifting price responsive bid ($\bar{\bar{p}}_{\mathrm{R}}$) can then be given as

$$\bar{\bar{p}}_{\mathrm{R}}(LPF)=\bar{p}_{\mathrm{R}}(LPF=0)-\bar{p}_{\mathrm{R}}(LPF) \tag{20}$$

Or more generally as the relative benefit or loss ($\bar{\bar{p}}$) given below

$$\bar{\bar{p}}(LPF)=\bar{p}(LPF=0)-\bar{p}(LPF) \tag{21}$$

Therefore, $\bar{\bar{p}}$ measures the saving of cost or loss or revenue resulted from demand shifting quantitatively by comparing the relevant weight average variable $\bar{p}$, relative to the case without any demand shifting. $\bar{\bar{p}}$ is defined by one of the set members below

$$\bar{\bar{p}}\in\{\bar{\bar{p}}_{\mathrm{R}},\bar{\bar{p}}_{\mathrm{T}},\bar{\bar{p}}_{\mathrm{D}},\bar{\bar{p}}_{\mathrm{P}},\bar{\bar{p}}_{\mathrm{G}}\} \tag{22}$$

It follows that the following relationship can be deduced

$$\bar{p}_{\mathrm{D}}=\bar{p}_{\mathrm{P}}\rightarrow\bar{\bar{p}}_{\mathrm{D}}=\bar{\bar{p}}_{\mathrm{P}} \tag{23}$$

which states that the saving of electricity cost of the system demand as a result of the introduction of demand shifting is obtained at the expense of a loss in revenue of the generators. On the other hand, the total relative benefit obtained by the supply side generators ($\bar{\bar{p}}_{\mathrm{TG}}$) can be given as

$$\bar{\bar{p}}_{\mathrm{TG}}=\bar{\bar{p}}_{\mathrm{G}}-\bar{\bar{p}}_{\mathrm{P}} \tag{24}$$

While the total relative benefit obtained by the demand-side ($\bar{\bar{p}}_{\mathrm{TD}}$) i.e. the price responsive and price taking bidders can be given as

$$\bar{\bar{p}}_{\mathrm{TD}}=\bar{\bar{p}}_{\mathrm{D}} \tag{25}$$

It should be noted that in a strict definition, $\bar{\bar{p}}_{\mathrm{TD}}$ must take account of the consumers’ gross surplus. However, it is intentionally ignored in (25) because the marginal benefit of consumption of the price responsive bidders is given an arbitrary large number and has no significant meaning. Furthermore, considering the marginal benefit of consumption into these equations would exaggerate the benefit of demand shifting. This is because the marginal benefit of consumption of the demand shifting bidder is assumed to be zero at LPF = 0 (where it submits a price taking bid instead). The total relative benefit obtained by all the participant groups ($\bar{\bar{p}}_{\mathrm{TA}}$) can be given by summing (26) and (27), which gives

$$\bar{\bar{p}}_{\mathrm{TA}}=\bar{\bar{p}}_{\mathrm{D}}+\bar{\bar{p}}_{\mathrm{G}}-\bar{\bar{p}}_{\mathrm{P}} \tag{26}$$

Substituting (23) gives

$$\bar{\bar{p}}_{\mathrm{TA}}=\bar{\bar{p}}_{\mathrm{G}} \tag{27}$$

Which states that the savings in operation cost of generators due to demand shifting is shared among all the market participants.

2 NUMERICAL RESULTS

The algorithm for the solution of the demand and supply matching problem has been applied to several scenarios to observe the effectiveness of the model. Emphasis is placed on the economical viability of demand shifting and also on evaluating its impact on the market. The test system used in the studies consists of 10 generating units with a total capacity of 5,545 MW. The peak load and minimum load are equal to 4,400 MW and 1,850 MW, respectively while the total system forecasted demand is 77,095 MWh, as given in Appendix Tab. 1 and Tab. 2.

2.1 Performance of Demand Shifting Bid

In this study, all the market participants are categorised into the following three groups: price responsive bidders of shifting type, price taking bidders and generators. We then analyse the impact of demand shifting from each of these individual groups' perspectives. For simplicity, it is assumed that there is only one demand shifting bidder and one price taking bidder respectively in this study. The demand shifting bid is modelled using the equations below

$$\bar{E}^1 = LPF \cdot \sum_{t=1}^{T} D_{\mathrm{F}}^t \Delta t \tag{28}$$

$$\bar{D}^{1,t} = \bar{E}^1 / \Delta t, \ \forall t = 1,..,T \tag{29}$$

$$\underline{D}^{1,t} = 0, \ \forall t = 1,..,T \tag{30}$$

$$MB_{\mathrm{Sg}}^{1,1,t} = p_{\mathrm{H}} = p_{\mathrm{L}}, \forall t = 1,..,T \tag{31}$$

$MB_{\mathrm{Sg}}^{k,j,t}$ is given a sufficiently high value so that its entire energy requirement defined in (28) will definitely be satisfied. As $p_{\mathrm{H}} = p_{\mathrm{L}}$, the price responsive part of system demand is perfectly elastic (i.e. $e \to -\infty$). In other words, the price responsive demand at each period will be shifted across the scheduling horizon in a way that minimises the system operating cost as the gross benefit of demand consumption is constant. This facilitates comparison of demand shifting benefits on equal ground among different system conditions (e.g. increasing LPF). The price taking bid is modelled as follow

$$D_{\mathrm{T}}^{z,t} = (1 - LPF) D_{\mathrm{F}}^t / V, \forall z = 1,..,V \tag{32}$$

Furthermore, to allow easier understand of simulation results, the generating units' no-load and start-up costs are omitted from the UC problem in this study.

The following diagrams in Fig. 2 to 5 show the effects of increasing price responsive demand on the system load profile and the market clearing prices (MCP). It can be observed that the system demand is shifted from high demand periods to fill up the valleys at both ends of the planning horizon.

While the reduction of system demand generally reduces MCP, the recovery of demand that fills up the two valleys can cause price increase at the corresponding periods. We observe a significant increase of MCP in periods such as 4 and 24, which is largely due to intensive demand shifting to these periods. On the other hand, the decrease in MCP due to demand reduction is relatively moderate, and at times no effect at all (e.g. t = 7 and 16). Therefore, demand shifting does not necessarily reduce MCP (likewise, demand recovery may not always increase MCP, although this is not shown on the figure). This is largely due to the discrete nature of generators' incremental prices. Nevertheless, demand shifting allocates MW to consumer in such a way that "energy neutrality" is preserved, i.e. the overall change in system demand at market clearance is zero (Fig. 3). This is in contrast with pumped storage technique as energy losses are incurred (due to evaporation of the exposed water surface and lossy energy conversion). The weighted average method formulated from to (27) is used to measure the impact of different levels of demand shifting on market participants quantitatively. The following figures summarises the effective costs (Fig. 6) and the relative savings (Fig. 7) of both the

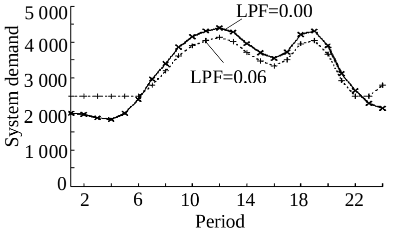

Fig. 2　System demand

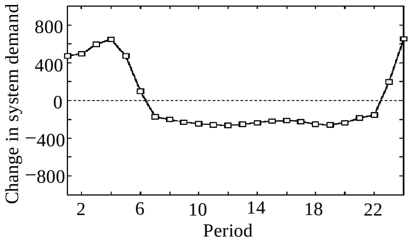

Fig. 3　Changes in system demand

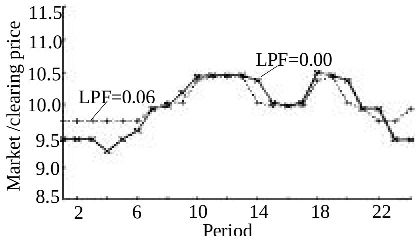

Fig. 4　Market clearing prices

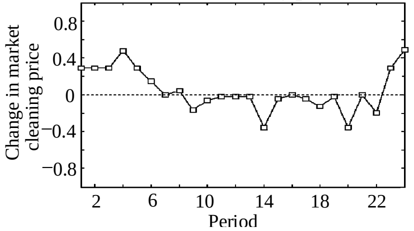

Fig. 5　Changes in market clearing prices

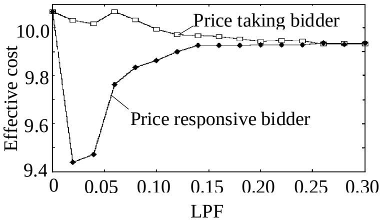

Fig. 6 Effective costs of the two demand-side bidders

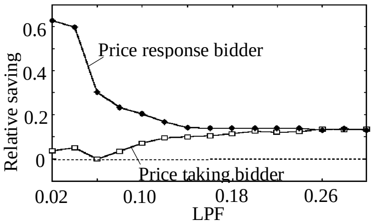

Fig. 7 Relative savings of the two demand-side bidders

shifting price responsive and price taking bidders respectively. It can be observed that the effective cost of price responsive bidder drops significantly as some demand becomes price responsive. However, the saving of the price responsive bidder (with respect to the case without any demand shifting) diminishes as the size of the demand shifting bid increases (i.e. LPF increases) as shown on Fig. 7.

On the other hand, the price taking bidder generally benefits from lower electricity prices as a result of the demand shifting as $\bar{\bar{p}}_{\mathrm{T}}$ is positive in most cases. This means that the benefit of lower wholesale prices as a result of the demand shifting behaviour has a certain "public good" aspect as other consumers do not necessarily need to respond to enjoy this benefit. Figure 8 summarises the relative benefits obtained by the demand-side bidders ($\bar{\bar{p}}_{\mathrm{TD}}$) and the supply side generators ($\bar{\bar{p}}_{\mathrm{TG}}$).

It can be observed that benefits of demand and supply are complementary while the generators are generally losers with increasing demand shifting level. The sum of the two plots of $\bar{\bar{p}}_{\mathrm{TD}}$ and $\bar{\bar{p}}_{\mathrm{TG}}$ in Fig. 8 gives the relative benefits of all participants ($\bar{\bar{p}}_{\mathrm{TA}}$) or the relative savings in system operating cost ($\bar{\bar{p}}_{\mathrm{G}}$), as shown in Fig. 9. As expected, the system is more efficient with increasing level of demand shifting. Nevertheless, the savings in system operating cost saturate as LPF increases, which is mainly due to the non-decreasing nature of the incremental production cost of generators.

2.2 Demand Shifting Bid VS Price-Volume Bid

This study compares the performance of the novel demand shifting bid against conventional price-volume bid for demand. The bidding behaviour of consumers that submit price-volume bid can be described by (33) and (34)

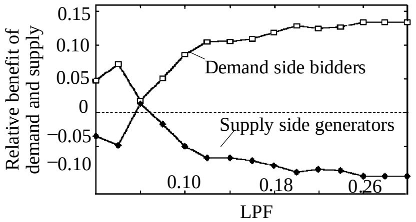

Fig. 8 Relative benefits obtained by demand and supply sides

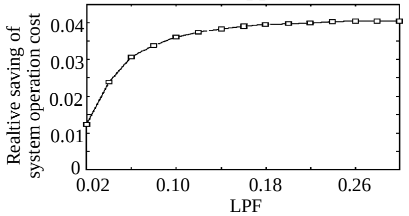

Fig. 9 Relative benefits obtained by all market participants

$$MB_{\mathrm{Sg}}^{k,1,t} = p_{\mathrm{L}} + (p_{\mathrm{H}} - p_{\mathrm{L}})(k-1)/M\,,\ \forall t = 1,..,T \tag{33}$$

$$D_S^{k,t} = LPF \cdot D_F^t / M\,,\ \forall k = 1,..,M \tag{34}$$

$$S_D = 1 \tag{35}$$

$$\underline{D}^{k,t} = \overline{D}^{k,t} = D_{\mathrm{S}}^{k,t} \tag{36}$$

$$\overline{E}^{k} = \sum_{t=1}^{T} D_{\mathrm{S}}^{k,t} \Delta t \tag{37}$$

Assume that there are $M = 10$ bidders and that the value they place on consuming electrical energy is time invariant. With these equations we can then construct a series of discrete bids that can be represented as a step function with a negative slope. It can also be seen that conventional price-volume bid is a special case of demand-shifting bid by specifying parameter values in (35) to (37) into the bid files (5) to (8), which effectively forces the demand to bidder *k* to be either 0 or $D_{\mathrm{S}}^{k,t}$. On the other hand, the consumers' that submits demand-shifting bid are assumed to behave in the manner described by to (31). With "price-volume" bidding method, in which the lowest bidding price of $MB_{\mathrm{Sg}}^{1,1,t}$ is 10.34 $/MWh while the highest is at 11.24 $/MWh, we have observed that at LPF = 0.05, some of these bids were rejected and caused the bidders to face unsatisfied demand. With shifting bid at $MB_{\mathrm{Sg}}^{1,1,t}$ = 10.34 $/MWh (and all other conditions unchanged), the entire demand requirement of these bidders would have been satisfied. The following Tab. 4 summarises the performance of the two bidding methods.

It can be deduced from the table above that

Tab. 4　Demand shifting bid vs conventional price-volume bid

Parameter	Bidding price	Effective cost	Total unsatisfied demand
Price -volume	10.34 to 11.24	10.24	34% of total energy requirement
Shifting	10.34	10.10	0

submitting a shifting bid is more beneficial, provided the consumers are flexible with the time period of consumption. It outperforms price-volume bid in both effective cost of consumption and managing of unsatisfied demand that has to be acquired in the balancing market.

3　CONCLUSION

A day-ahead market clearing tool that maximises the social welfare has been presented. The tool offers consumers the opportunity to save consumption cost by submitting a shifting bid, provided they are flexible with the timing of consumption. This bidding mechanism is useful in managing the risk of going unbalanced after the gate closure of day-ahead market, especially if the day-ahead prices are volatile. The market clearing prices tend to reduce with increasing level of demand shifting, which benefits all bidders even if they do not participate in shifting activities. It is also evident from studies that demand shifting improves the economic efficiency of the day-ahead market as the effective costs of serving system demand tends to reduce. Studies have shown that shifting bid outperforms conventional price-volume bid in both management of unsatisfied demand and effective cost of energy consumption. It has also been observed that a substantial amount of savings of the system operating cost are transferred to the demand-side with increasing level of demand shifting. In this regard, the extent to which the demand-side bidders are able to "game the system" by bidding strategically under the proposed auction market design is worth investigating in future research work.

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APPENDIX

Tab. 1　Offering prices of the 10-unit system

Unit	$\underline{P}^i$	$P_{\mathrm{E}}^{i,1}$	$P_{\mathrm{E}}^{i,2}$	$\overline{P}^i$	N_{G}^i	s_{G}^1	s_{G}^2	s_{G}^3	K^i	IO^i
1	50	100	150	200	200	820	9.023	0.001 13	750	–1
2	75	150	200	250	250	400	7.654	0.001 60	625	–7
3	110	200	300	375	375	600	8.752	0.001 47	550	–1
4	130	230	300	400	400	420	8.431	0.001 50	650	5
5	130	200	350	420	420	540	9.223	0.002 34	650	–2
6	160	300	500	600	600	175	7.054	0.005 15	950	1
7	225	300	500	700	700	600	9.121	0.001 31	900	–8
8	250	400	600	750	750	400	7.762	0.001 71	950	6
9	275	400	600	850	850	725	8.162	0.001 28	950	2
10	300	500	800	1 000	1 000	200	8.149	0.004 52	825	–4

Tab. 2　Load profile for the 10-unit system

Period	D_{F}^t	Period	D_{F}^t	Period	D_{F}^t
1	2 025	9	3 850	17	3 725
2	2 000	10	4 150	18	4 200
3	1 900	11	4 300	19	4 300
4	1 850	12	4 400	20	3 900
5	2 025	13	4 275	21	3 125
6	2 400	14	3 950	22	2 650
7	2 970	15	3 700	23	2 300
8	3 400	16	3 550	24	2 150

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作者简介：

Daniel Kirschen，Male，professor at the university of Manchester and head of the electrical energy and power systems research group.He is a fellow of the IEEE and a fellow of the IET.

（实习编辑　王晔）