Joseph H. Yan, Gary A. Stern, Peter B. Luh, and Feng Zhao

payment versus bid cost

minimization in ISO markets

CURRENTLY, IN DEREGULATED wholesale electricity markets (Pennsylvania-Jersey-Maryland Interconnection, New York Independent System Operator, Independent System Operator New England, Midwest Independent System Operator, Electric Reliability Council of Texas, and California Independent System Operator) in the United States (e.g., the day-ahead and real-time energy markets), market participants submit energy and ancillary service bids for their supply or demand bids to an independent system operator (ISO), and the ISO runs auctions to determine the selections of resources, the levels of output from the selected resources, and the market clearing prices (MCPs) or locational marginal prices (LMPs). (For simplicity of presentation, MCP is used in the remaining part of this article to illustrate the key ideas.) Markets are then settled based on the MCPs, i.e., selected supply bidders are paid and selected demand bidders are charged at the MCPs regardless of their bid prices. This "pay-at-MCP" settlement scheme has been widely accepted by the U.S. electricity markets as opposed to the "pay-as-bid" scheme, where the payments for selected bids are determined as their bid costs. Under the pay-at-MCP payment scheme, however, ISOs in the United States currently minimize the total "as-bid" cost in their auctions to determine the bid selections and the generation levels of selected bids. This "bid-cost minimization" auction is inconsistent with the pay-at-MCP settlement, i.e., the minimized bid cost in the auction process is not the same as the payment cost made during the settlement process. As a result of this inconsistency, the total payment cost could be significantly higher than the minimized "as-bid" auction cost. To eliminate this inconsistency, an alternative auction mechanism that directly minimizes the payment cost ("payment-cost minimization") has been discussed, and significant progress towards an implementable solution has been made in recent years. In the following, a brief history of the debate on auction objective functions in ISO markets is first presented along with the flaws of the bid-cost minimization auction. Then, the challenges of the payment-cost minimization auction are presented, followed by a summary of recent progress in addressing these challenges. Lastly, several questions and concerns regarding payment-cost minimization are discussed.

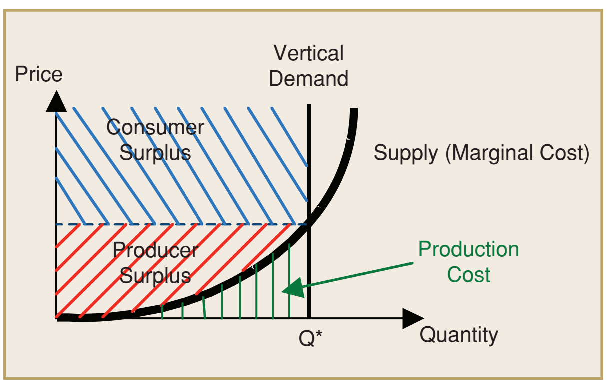

figure 1. The supply and demand curves. Social welfare is defined as the summation of consumer surplus and producer surplus. With fixed (or vertical) demand, the maximization of social welfare is equivalent to the minimization of the production cost.

What's the Issue?

Before deregulation, vertically integrated local utilities managed the entire process of power generation, transmission, and distribution to serve their customers. Classical unit commitment and economic dispatch models were run to determine generation schedules. The objective of these models was to select a set of generation units and their generation levels to minimize the total production cost (fuel costs plus variable operations and management) while satisfying the demand and other requirements (e.g., reserve requirements). Under fixed demand (e.g., the forecast load), the minimization of production cost was then equivalent to the maximization of social welfare, as illustrated in Figure 1.

The unit commitment and economic dispatch problems belong to a class of mixed-integer programming problems with the objective of minimizing production cost subject to system demand, unit capacity, reserve requirements, and other

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individual unit constraints. These problems are generally considered to be NP-hard. However, due to their separable structure, they can be efficiently solved by using decomposition and mixed-integer programming techniques, and there are well-developed software packages readily available to solve them. (An optimization problem is separable and can be decomposed into subproblems if the objective function and the constraints are additive in subproblem decision variables.) The key idea of decomposition is to first relax system-wide demand and reserve constraints that couple different units and then decompose the problem into individual unit subproblems to be solved iteratively. The mixed-integer programming techniques include branch-and-bound and cutting plane methods.

Since deregulation, ISOs have run centralized forward energy auctions in order to select generation bids to meet the demand and other requirements. An important question immediately follows: What should be the appropriate settlement scheme? In other words, how should the payments be determined? Two options—"pay-as-bid" versus "pay-at-MCP"—have been extensively discussed. The pay-as-bid approach settles the payment based on bid costs, while the pay-at-MCP approach uses the MCP for settlement. Abundant research has been done on the settlement issue, and it has been concluded that pay-as-bid "would do consumers more harm than good" (Blue Ribbon Panel Report, 2001). The primary reason for this conclusion is that under the pay-as-bid settlement scheme, market participants would bid substantially higher than their marginal costs (since there is no incentive for participants to bid their operating cost) to try to increase their revenue and, thus, offset and very likely exceed the expected consumer payment reduction. As a result, currently all ISOs in the United States adopt the pay-at-MCP principle.

While the market settlement scheme has been extensively studied, little attention has been paid to the auction mechanism. Currently, ISOs minimize the total bid cost in their auctions. The objective function for a simplified auction can be formulated as

$$\min_{\{p_i,(t)\}} J,$$

$$\text{with } J \int \sum_{t=1}^{T} \sum_{i=1}^{I} \{O_i(p_i(t), t) + S_i(t)\}, \tag{1}$$

where $p_i(t)$ is the selected megawatt level of bid i at hour t, $O_i(.)$ is the bid cost curve of bid i, and $S_i(t)$ is the start-up cost of bid i at hour t. [Note that $S_i(t)$ is incurred if and only if bid i is turned from "off" status at hour $t-1$ to "on" status at hour t.] The problem is very similar to a traditional unit commitment problem, only with bid costs replacing

Pay as Bid or Pay as Settled— Why Is There a Difference?

The last several articles in this column have examined electric markets in other parts of the world. These markets are designed from very distinctive viewpoints, from representing the customer to aggregating the sellers. Markets should be designed according to the total set or rules from bidding through settlement. Settlement is the function to resolve the differences between the bids submitted and the actual operation of the system over time, including all charges incurred to implement the contracts. The present article discusses a change in the market design to harmonize the settlement process with the bid selection process.


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The market settlements rules are implemented to generate appropriate price signals. The price signals are communicated to the market participants via a complex system of settlements rules implemented as part of a particular market design. The full set of rules is between 50 and more than 100 for some markets. A particular implementation of the detailed rule set is best understood if the rules are categorized into subsets, which might run into the high hundreds. The Electric Reliability Council of Texas Settlement Protocols described 42 rules. The amended California IS0 marked design MD02 describes about 180 settlement business rules.

This system of rules covers the complete requirements needed to financially balance the market, taking as inputs product prices; all traded product volumes; grandfathered contracts; reliability must run (RMR) contracts; various market conditions such as transmission congestion, outages, generation, and transmission losses; and imports and exports on the boundary interfaces.

The price signals get propagated back to the market participants after being run through the set of settlement rules and, depending on the specific market events and conditions, the participants are being invoiced for the corresponding debits or credits incurred by them participating on the market.

The correctness of the complex system of rules is crucial to the successes of the market design. However, analytically proving this correctness could be a daunting task given the complexity of a particular market implementation. Therefore, a way must be devised to decisively prove that the market implementation is designed to properly telegraph market signals to the participants, which is also economically easy to implement and able to be applied to a wide variety of market designs. This article attempts to resolve the bids with the settlement by an alternative formulation of the auction process.

—Gerald Sheblé
Associate Editor, Business Scene

production costs in the objective function. As a result, the existing software packages for unit commitment and economic dispatch can be readily adapted to solve the bid-cost minimization problem. However, a basic question about the above auction objective (1) is: Why do we minimize the "as-bid" cost in auctions while the "pay-as-bid" settlement scheme has already been rejected?

Actually, corresponding to the two settlement schemes, there are also two options for the auction mechanism: "bid-cost minimization" and "payment-cost minimization." Unlike the bid cost in (1), the payment-cost minimization auction minimizes the consumer payment cost, i.e.,

$$\min_{\{\mathrm{MCP}(t)\},\{p_i(t)\}} J,$$
$$\text{with } J \triangleq \sum_{t=1}^{T}\sum_{i=1}^{I}\{\mathrm{MCP}(t)p_i(t) + S_i(t)\}. \tag{2}$$

It is, therefore, natural to expect a debate on the auction objectives similar to that on the settlement scheme. However, there is only limited discussion of payment-cost minimization, and the adoption of bid-cost minimization was carried out without much justification. We believe the auction issue at least deserves the same level of debate the settlement issue received. Furthermore, one focus for the study should be the consumer benefit since it is the major objective of deregulation and has been used to justify the pay-at-MCP settlement scheme.

Despite the lack of debate regarding the auction mechanism, one justification for bid-cost minimization is that the auction would maximize the social welfare. The question, however, is whether or not the market participants' bid costs really and fully reflect production costs. If the answer is yes, then the bid-cost minimization should be adopted and no debate on the auction mechanism is needed. If the answer is no, then we need to think further about the current use of the bid-cost objective function. Unfortunately, many studies have provided the evidence that generation bid prices are often above marginal cost. One study concluded that sellers either submitted bids at prices significantly above marginal cost of their generation unit or withheld part of the available capacity from being bid or scheduled into the market. Another study pointed out that, in summer 2000, the California wholesale electricity expenditure was US$8.98 billion, up from US$2.04 billion in summer 1999, and that 59% of this increase was due to market power. A third study showed that there was overwhelming evidence of a significant market power effect reflected in wholesale market prices in California during summer 2000. Many researchers concluded that generators bid higher and that their bids were unrelated to production costs.

Furthermore, many ISOs (e.g., PJM and NY ISO) allow the existence of virtual bids in their day-ahead energy markets under their current market rules. These virtual bids are purely financial and have little to do with the production costs of physical generation resources. Consequently, minimizing the bid cost, including that of the virtual bids, leads nowhere close to social welfare maximization. All the above results make the maximization of social welfare under bid-cost minimization unreachable.

What's Wrong with Bid-Cost Minimization?

As discussed above, ISOs in the United States currently use the pay-at-MCP settlement scheme but minimize the as-bid cost in the auction process. This inconsistency between payment cost and minimized bid cost may lead to dramatically high consumer payments, as illustrated by Example 1.

Example 1

Consider an auction for one hour with four supply bids from four units and system demand of 100 MWh. For simplicity, transmission constraints and reserve requirements are not considered. Also, the startup costs of selected bids are assumed to be fully compensated. The supply bid prices and characteristics of the four units are summarized in Table 1.

Under bid-cost minimization, the cheap units, A and B, will be selected for a total capacity of 90 MW, and the remaining 10 MW (100 MW − 90 MW) goes to unit C, with additional bid cost of US$1,020 ($10 \times 100 + 20$), instead of unit D, with additional bid cost of US$2,300 ($10 \times 30 + 2{,}000$). This leads to a minimized total bid cost of US$2,370, and the MCP is set by the unit C price (US$100/MWh). Since the pay-at-MCP settlement scheme is used, every selected bid is paid at the MCP. This leads to a total payment cost of US$10,020, which is significantly higher than the minimized bid cost. It can be seen that the high payment cost is caused by the selection of unit C (having a lower bid cost) that sets a high MCP. The above bid-cost minimization results are presented in Table 2.

Now consider the solution under a payment-cost minimization auction. The results are presented in Table 3.

It can be seen that the payment-cost minimization auction results in different unit selections than the bid-cost minimization solution. Unit D is selected since it sets a lower MCP and thus lowers the consumer payment cost as opposed to the selection of unit C. The different selections of units under the two auction schemes are illustrated in Figure 2.

It can be seen from Figure 2 that the selection of high-price unit C under bid-cost minimization is caused by ignoring the system-wide cost impact of its high bid price (US$100/MWh). As a result, consumers pay a significantly higher amount in the settlement process. This can also be used to explain the price spikes caused by the selection of some small-sized and high-priced units in the bid-cost minimization markets. In contrast, payment-cost minimization considers the actual payment cost, and thus would be less likely to select those high-priced units, thereby reducing the clearing price spikes. Further study of the bidding behaviors of market participants has shown more interesting results. One of our findings is that suppliers are more likely to bid high prices for their small units under bid-cost

table 1. Bids of a four-unit 1-h example.

	Capacity (MW)	Bid Price ($/MWh)	Startup Cost ($)
Unit A	45	10	0
Unit B	45	20	0
Unit C	12	100	20
Unit D	80	30	2,000
System Demand = 100 MWh			

table 2. Solution of bid-cost minimization auction for Example 1.

	Bid-Cost Minimization Auction Solution				Settlement At MCP = US$100/MWh		
	Selected MWh	As-Bid Energy Cost (US$)	Startup Cost (US$)	Subtotal (US$)	Energy Payment (US$)	Startup Payment (US$)	Subtotal (US$)
Unit A	45	450	0	450	4,500	0	4,500
Unit B	45	900	0	900	4,500	0	4,500
Unit C	10	1,000	20	1,020	1,000	20	1,020
Unit D	0	0	0	0	0	0	0
Total	100	2,350	20	**2,370**	10,000	20	**10,020**

minimization compared to payment-cost minimization. This can be used to explain the notorious hockey-stick bidding behaviors observed in current markets. For example, a supplier having a portfolio of generation capacities may choose to speculate on its small units, as illustrated in Figure 3.

Challenges of Payment-Cost Minimization

In spite of the advantage of payment-cost minimization for reducing consumer payments, many challenges remain to be addressed. The first challenge is how to solve the problem in view of the inseparable structure of a payment-cost minimization problem. While the solution may seem obvious for the simple Example 1, it is actually very difficult to solve larger problems with more units and more hours since the number of possible unit selections is an exponential function of the number of units and hours. More importantly, unlike the bid-cost minimization problems where MCPs are byproducts of the minimization, a salient feature of payment-cost minimization is the involvement of MCPs in the auction objective function (2). This makes the payment-cost minimization problems inseparable in individual bids, i.e., there exists cross-product terms between MCPs and bid variables. As a result, existing approaches for unit commitment and economic dispatch cannot be used to solve the payment-cost minimization problems. Also, a comprehensive comparison of the two auction schemes needs to be done. This greater complexity associated with solving the problem may also explain the lack of debate over the auction mechanism, as described

table 3. Solution of payment-cost minimization auction for Example 1.

	Payment-Cost Minimization Auction Solution				Settlement At MCP = US$30/MWh
	Selected MWh	Energy Payment (US$)	Startup Payment (US$)	Subtotal (US$)	
Unit A	45	1,350	0	1,350	
Unit B	45	1,350	0	1,350	Consistent with the auction solution
Unit C	0	0	0	0	
Unit D	10	300	2,000	2,300	
Total	100	3,000	2,000	5,000	

previously. The above challenges have been addressed in our recent study and ongoing research, as presented in the following section.

Recent Progress and Ongoing Research on Payment-Cost Minimization Auctions

To obtain insights on solving payment-cost minimization, a simplified market model with single block supply bids and fixed demand over the planning horizon is considered first for study. Ancillary services and transmission constraints are not included, and selected bids are assumed fully compensated for their startup costs. MCPs are defined as the highest price of selected bids. These MCPs are part of the decision variables since they explicitly occur in the payment cost objective (2). As a result, the definition of MCP needs to be operationalized in the problem formulation. Our approach is to incorporate "MCP-bid price" inequality constraints (i.e., MCP should be greater than or equal to bid prices with zero prices defined for those bids that are not selected) into the payment-cost minimization formulation. Since the problem cannot be separated into individual bid subproblems with the existence of the cross-product terms between MCP and unit generation levels in (2), traditional Lagrangian relaxation techniques cannot be directly applied.

Our method is to use an innovative "surrogate subgradient" method within an augmented Lagrangian relaxation framework to overcome the difficulties caused by the problem inseparability. The key idea of the method is that the relaxed problem does not need to be solved optimally as required by the traditional subgradient method. Rather, an approximate solution to the relaxed problem is sufficient if the "surrogate optimization" condition is satisfied, implying that the "surrogate subgradient" forms an acute angle with the direction toward the optimal multiplier vector. The relaxed problem is thus optimized with respect to a particular supply bid one at a time until the condition is satisfied. In optimizing a bid, other variables may have to be adjusted to satisfy the surrogate optimization condition. An augmented Lagrangian technique that adds quadratic penalty terms into the traditional Lagrangian is used to reduce solution oscillation. Numerical testing results demonstrate that the method is effective and near optimal and that, for a given set of supply bids, the resulting payment cost is significantly lower than that obtained by minimizing the total bid cost. The above augmented Lagrangian relaxation and surrogate optimization framework has also been extended to incorporate market practices such as demand bids and partial capacity cost compensation.

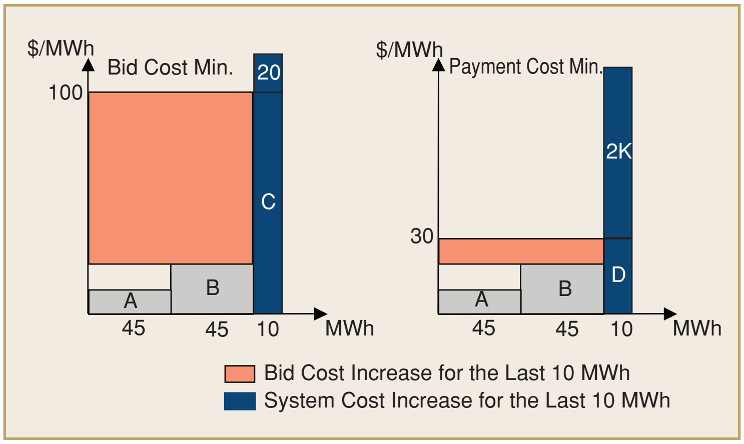

figure 2. Different solutions under bid-cost minimization and payment-cost minimization.

In addition to energy, ancillary services (e.g., regulation, spinning reserve, and nonspinning reserve) also play an important role in power operation and system reliability and are often procured through auctions. There are two ways to conduct ancillary service auctions: one is to conduct the energy auction first and then the ancillary services auction (sequential optimization); the other is to co-optimize the energy and ancillary services (simultaneous optimization). The latter has been shown to yield better solutions in our study, and it is adopted in the payment-cost minimization problem. With ancillary services, the costs that consumers have to pay include those for both energy and ancillary services. In addition, since ancillary services are competing against energy usage for the same generation capacity and the provision of some ancillary services (e.g., regulation and spinning reserve) requires the units to be "on," the energy and ancillary services are coupled in a complicated manner. The payment-cost minimization for simultaneous auction of energy and ancillary services has been solved by extending the augmented Lagrangian and surrogate optimization framework developed earlier by our university collaborators. We are currently conducting more numerical testing and preparing a journal paper.

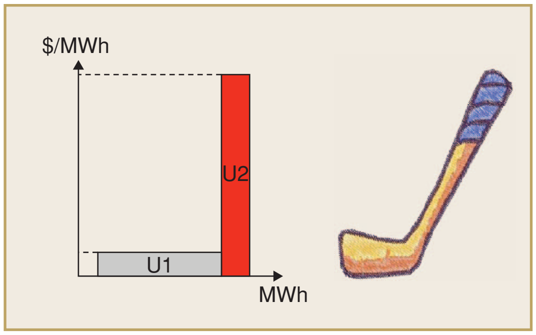

figure 3. Illustration of hockey-stick bidding.

Since standard market design (SMD) and most ISOs have adopted LMPs, we have also solved the LMP payment-cost minimization problem with transmission capacity constraints. The consideration of transmission constraints complicates the problem by entailing power flow limitations and introducing LMPs. For simplicity, transmission loss is not considered and dc power flow is used. LMPs are defined by "economic dispatch" for the selected supply bids. To characterize LMPs that appear in the payment-cost objective function, Karush-Kuhn-Tucker (KKT) conditions of economic dispatch are established and embedded as constraints. The reformulated problem is difficult in view of the complex role of LMPs and the violation of constraint qualifications caused by the complementarity constraints of KKT conditions. Our key idea is to use a regularization technique to manage the violation of constraint qualifications and then extend the surrogate optimization framework. Specific techniques to satisfy the "surrogate optimization condition" in the presence of transmission capacity constraints are developed. Numerical testing results of small examples and the IEEE Reliability Test System with randomly generated supply bids demonstrate the effectiveness of the method.

The above results concentrate on the development of solution methodologies for payment-cost minimization problems with various market setups. Testing results show that with the same set of supply bids, payment-cost minimization leads to reduced consumer payments compared to bid-cost minimization. However, the cost savings may not be realized since market participants may bid differently under the two auction mechanisms. This leads to the need to investigate the strategic behaviors of power suppliers. In our recent effort, the bidding behaviors of suppliers under the two auction mechanisms are studied by using a game theoretic framework. Market participants are assumed to have competing objectives, and a supplier maximizes his/her profit by selecting an appropriate bidding strategy from finite strategy choices. Since each participant's bidding decision depends on the other participants' decisions, a matrix game is formed for each auction method and a Nash equilibrium is used as the solution concept. Simple two-supplier Nash games with continuous strategies are first analyzed to provide insights. General matrix Nash games are then solved by using the concept of approximate Nash, with our auction algorithms developed earlier serving as the core. Testing results demonstrate that, in general, payment-cost minimization leads to significant payment reduction with relatively small increases in production cost and bid cost as compared to bid-cost minimization. Furthermore, testing examples demonstrate that hockey-stick bidding is less likely to occur under payment-cost minimization. Our ongoing research includes the study of continuous games for the two auction methods and the investigation of broader economic implications.

Discussion

Since the payment-cost minimization auction was brought into discussion, many insightful questions and concerns have been raised. For example, our study shows that the consumer savings are obtained at the cost of reducing generation revenues. Therefore, an important question is: Would this cause revenue adequacy difficulties (i.e., generation companies do not make enough money from the energy markets to cover both their production costs and capital costs) and thus remove the incentives to build new generation? While the payment-cost minimization auction would in general reduce generation companies' revenues from the ISO day-ahead market compared to the bid-cost minimization auction, the answer to this question actually lies beyond the day-ahead market itself. It is acknowledged that the problem of generation companies not getting enough revenue from the market to recover their costs already exists in today's markets with bid-cost minimization. We therefore believe the source of the problem is that the short-term energy market alone is not sufficient to cover both the production costs and capital costs of generators or to bring long-term incentives for new generation. As a result, the revenue shortage problem should be resolved within a context including capacity markets, long-term contracts, etc.

Other concerns, such as environmental impacts of the payment-cost minimization auction, have also been raised. Example 1 shows that payment-cost minimization selects Unit D with low price and high startup cost (e.g., an outdated coal-burn generator) rather than the small Unit C with high price and low startup cost (e.g., new-tech jet-engine generator). The concern is that Unit D selected under payment-cost minimization might cause more pollution than Unit C. While the selection of Unit D shows nothing wrong from an optimization point of view, a response to the environmental concern may be to include the environmental cost in the objective function, and this depends on the market rules. Still, the auction objective should be to minimize the total payment cost, including environmental payment costs if required by market rules.

The above questions are examples of the ongoing discussions. They show that the issues of the auction objective are being brought into wider discussions. We believe these discussions to be valuable to various groups.

Conclusions

Whether ISOs should minimize the total as-bid cost or the total payment cost in their auctions is a crucial decision for both consumers and generation companies since the selection will affect both the bids and the MCPs. Further, the MCPs have financial impacts on forward transactions outside the ISO markets as well as on long-term investment decisions. Illustrative examples have demonstrated that for the same set of bids, payment-cost minimization leads to payment reductions compared to the bid-cost minimization technique that is currently used by ISOs. Considering that the total value of electricity purchased in these systems is in the billions of dollars annually, even a very small percentage of payment-cost reduction will result in millions of dollars in annual savings for consumers. This article summarizes our recent developments in the solution methodology of payment-cost minimization and the economic analysis of the two auction methods. Furthermore, topics such as revenue adequacy implications are brought into discussion. Generally speaking, the research on the appraisal of the two auction methods is still at the early stages, and we believe that a comprehensive study of the two auction methods is highly valuable for both researchers and industrial practitioners. We hope this article can initiate more serious debate among researchers and stakeholders as to which objective should be used in ISO markets.

For Further Reading

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PES General Meeting, 20–24 July, Pittsburgh, Pennsylvania, USA, contact General Chair David J. Vaglia, davevaglia@ieee.org, Technical Program Chair Kalyan Sen, senkk@ieee.org (sponsored by PES).

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the business scene *(continued from page 36)*

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