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Incentive compatible pool-based electricity market design and implementation: A Bayesian mechanism design approach ☆

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HIGHLIGHTS

- A novel pool-based electricity market mechanism is proposed in this paper.
- The mechanism includes merit order rule, unit-dispatching rule and settlement rule.
- Incentive compatibility, individual rationality and payment-cost minimization hold.
- This customized mechanism can encourage truthfulness and eliminate tacit collusion.

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ABSTRACT

Under conditions of imperfect competition, the issue of asymmetric information, which has not been effectively managed and settled until now, has been one of the most significant problems of the pool-based electricity market, both in theory and practice. Electricity generation companies expect to maximize their profits and control the market price by strategically bidding and their offers will necessarily deviate from the true marginal costs. These practices would result in great losses of market efficiency and incur much more payments from the consumers than actually needed. Therefore, this paper uses the analytical paradigm of economic mechanism design theory to deduce and design a customized pool-based market mechanism, which simultaneously satisfies three major properties of mechanism design theory: incentive compatibility, individual rationality and payment cost minimization. Then, several issues associated with the operational principle and implementation of this innovative mechanism are discussed and examined in detail. Finally, the results of numerical examples and case study validate the effectiveness of the proposed mechanism, which can encourage truthfulness and eliminate tacit collusion, even when there is a tight market or transmission congestion with pivotal suppliers.

1. Introduction

At present, centralized pool-based auction mechanisms are generally established in major electricity markets operated by PJM, ERCOT, and CAISO in North America [1–3], BETTA in Great Britain [4,5] and Nord Pool Spot in Nordic Europe [6]. The pool-based real-time markets are often taken as the last resorts to balance the power systems [7], generating real-time prices to provide signals for economic activities and future investment decisions in the market. However, both theory and practice have shown that the trading mechanisms of current pool-based markets, cannot properly address several vital problems such as asymmetric information and tacit collusion under conditions of imperfect competition, not to mention when tight supply–demand relationships, transmission congestion or a high level of market concentration happen. Even with enough generation capacities, the market prices may still abnormally soar and fluctuate [8–14]. Actually, these phenomena mainly result from the fact that the current mechanisms fail to satisfy the requirement for incentive compatibility [15–19]. Generation companies (Gencos) that are rational tend to maximize their profits through strategic bidding instead of offering the true marginal cost [20–24], which inevitably causes a significant loss of market efficiency and adversely affects the operation of the electricity market and power system [25,26]. Therefore, various complementary measures, such as offering cap, clearing price cap, scarcity pricing, and Three Pivotal Test, which have been introduced in the PJM energy markets, have been adopted by market operator (MO) to mitigate price spikes and reduce the risks of price

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volatilities [27]. Nevertheless, most of these methods are essentially mandatory market interventions and cannot be shown to be theoretically incentive compatible.

Meanwhile, mechanism design (MD) theory, which aims to realize incentive compatibility, has become a powerful tool for providing scientific guidance for designing the electricity market mechanism and alleviating the adverse impact of information asymmetry between MO and market participants. As an emerging sub-discipline of microeconomics, MD has rapidly developed over the past two decades and is generally applied in numerous areas such as monopoly pricing, optimal taxation, contract theory, principle agent theory, and auction theory. In general, MD provides a series of theories and approaches to solve problems related to whether and how to design a mechanism, institution or rule to achieve the designer's goal in a comparatively real economic environment, which is characterized by free choice, voluntary exchange, asymmetric information and decentralized decision making. Therefore, MD can always make individual rationality consistent with collective rationality [28].

Several scholars have attempted to introduce the idea of incentive compatibility to the electricity market design. Among these studies, some researchers directly applied the Vickery–Clarke–Groves (VCG) mechanism in practice. Ref. [29] uses the VCG mechanism to design a double auction mechanism with consideration of the non-convex generation cost curve and the non-concave consumer utility curve, which can make telling the truth a weak dominant strategy equilibrium. However, as indicated by the authors, this mechanism cannot achieve budget balance and prevent market participants from collectively colluding and cheating. In [30], the MO clears the pool-based market without respect to the network constraints in the first stage and subsequently redesigns the settlement rule based on the VCG concept. The MO would give each Genco both generation payment and transfer payment. The latter is related to the participants' contribution to the social welfare and the whole settlement rule could ensure the MO to balance the budget ex post and enhance social welfare to a certain extent. However, similar to [29], this mechanism cannot prevent private conspiracy either. Ref. [31] establishes a VCG-based demand-side management mechanism for utility companies and can fulfill user truthfulness and nonnegative transfer. However, this project fails to provide practical solutions to relevant problems such as weak dominant incentive compatibility, complex operational procedures, budget imbalance and tacit conspiracy [32].

Certain papers approach these problems from another perspective, using game theory and economic MD theory to design unusual electricity market mechanisms. Depending on the centralized market clearing results of security constrained economic dispatch (SCED), an incentive compatible settlement rule is proposed and contains two types of payments: compensation for the cost of generation and compensation for truthful bidding [33]. Nonetheless, the individual rationality and payment cost minimization properties in [33] are not strictly demonstrated in theory. In addition, the computation method for the expected unit's production quantity in the formulation of information compensation is not explicitly introduced, and the fundamental principle, which the expected generation output would decrease when the unit's submitted bids increase, is not certified. In [34], a so-called Generator Semi-randomized Matching (GSM) mechanism based on signaling game theory is examined to avoid the deficiencies of the traditional High-Low matching bidding mechanism. The simulation results show that the GSM mechanism can reduce the clearing price and increase the total transaction volume to some extent. However, the incentive compatibility of GSM is not precisely confirmed in this paper. In accordance with MD theory, an incentive compatible, individually rational and nonlinear pricing contract for effective demand management is developed for utility companies in [35]. However, the purpose of this incentive contract is to maximize the utility's profit instead of minimizing the consumers' payment cost, and the detailed design process is not presented.

Therefore, how to design a practical incentive compatible pool-based market under conditions of incomplete information and imperfect competition remains challenging and important for electricity market institution constructing and rulemaking. A theoretically ideal electricity market should be able to encourage the market participants to offer their true marginal cost and rationally compete, eliminate tacit conspiracy, and ultimately reduce the consumers' payments. To achieve these goals, this paper uses the analytical framework of MD theory [36–39] to design an innovative and customized pool-based market mechanism for the electricity generation side. This new mechanism is strictly deduced and mathematically formulated to be an Incentive compatible, Individually rational and Payment cost minimization Bayesian Mechanism (IIPBM).

Generally, the main idea of IIPBM is to encourage the Gencos to submit truthful bids using three rules: the merit order rule, unit-dispatching rule and settlement rule. The Gencos that bid abnormally high prices in the pool-based market are punished with a lower priority to generate by the merit order rule, are assigned less generation output by the unit-dispatching rule, and are rewarded with less "information rent" by the settlement rule, which are also the physical meanings and core ideas of the three rules. These rules are well designed and strictly deduced with the guidance of MD theory to guarantee that the Gencos can maximize their profits only when they make truthful bids, which indicates that truthfulness is the Bayesian equilibrium of the IIPBM. Moreover, the profit of each Genco is not affected by other Gencos' bidding performance using the settlement rule of the IIPBM, which helps prevent private collusion. Furthermore, to make the IIPBM more easily understood and accepted by market participants and seamlessly integrated into the currently operating market mechanisms such as the marginal clearing price mechanism (MCP) or pay as bid mechanism (PAB), this paper also investigates several issues related to the implementation of the IIPBM, and the operational procedure is designed to be coordinated with current market mechanisms. Such institution designs are intended to make the IIPBM a "plug-and-play" complementary market module or an amendment to the currently operating energy market.

Specifically, the remainder of this paper is organized as follows. The analytical framework of the IIPBM is presented in Section 2. The institutional design of the IIPBM is rigorously investigated and three operational rules, including the merit order rule, unit-dispatching rule and settlement rule, are successively derived in Section 3. The operational principle and implementation of the IIPBM are thoroughly investigated in Section 4. Numerical examples are analyzed and discussed to verify the effectiveness and superiority of the IIPBM in Section 5. Finally, the conclusions are summarized in Section 6.

2. Analytical framework of the IIPBM

Essentially, MD is intended to be the inverse of the non-cooperative game with incomplete information and centers on the optimal choice of the game rules on the premise that the equilibrium is determined in advance. Moreover, the first principle to which MD should always adhere is the effective incentive. In 1972, Leonid Hurwicz first proposed the key notion of incentive compatibility. This concept means that a truthful report of private information is an optimal reaction for each participant. In addition, the formulation of the revelation principle, which was introduced by Roger Myerson, and the development of implementation theory,