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Consumer payment minimization under uniform pricing: A mixed-integer linear programming approach

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HIGHLIGHTS

- We examine the consumer payment minimization problem by mixed-integer linear programming.
- Quadratic and piecewise linear supply offers, and inter-temporal constraints are modeled.
- As a salient feature, no heuristic manipulation or control parameter tuning are required.
- Optimal or high-quality near-optimal solutions are attained in moderate computing times.
- Inter-temporal constraints enlarge payment reductions with slight cost increases.

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ABSTRACT

This paper presents a multi-period auction for a day-ahead pool-based electricity market in which consumer payment for energy is minimized under uniform pricing. This optimization problem has been recently characterized as a non-separable, non-linear, mixed-integer, and combinatorial problem for which exact solution techniques are unavailable. We present a novel approach suitable for existing mixed-integer linear solvers. A major contribution of this paper is the explicit characterization of uniform market-clearing prices as primal decision variables. The proposed methodology allows considering both quadratic and piecewise linear supply offers. In addition, the market-clearing procedure also takes into account inter-temporal operational constraints such as start-ups, ramp rates, and minimum up and down times, which may be part of generation offers. This approach provides the system operator and market agents with a valuable tool to assess consumer payment minimization versus currently used declared social welfare maximization. This conclusion is backed by simulation results obtained with off-the-shelf software.

1. Introduction

The electric power industry is currently immersed in a competitive context wherein market-clearing procedures play a crucial role. In a pool-based electricity market for energy, the independent system operator (ISO) collects the offers and bids respectively submitted by producers and consumers. Generation offers may comprise not only economic terms but also technical features such as production limits, ramp rates, and minimum up and down times. Based on the application of a market-clearing procedure, the ISO determines the market-clearing prices, the power productions, and the consumption levels for all time periods [1,2]. Market-clearing procedures should be transparent, fair, and incentive-compatible, while allowing investment cost recovery [1]. Additionally, they should preserve the privacy of the corporate information belonging to market participants.

The market-clearing procedures implemented in current electricity markets [2–5] are essentially identical to the unit commitment problem that is solved in centralized non-competitive power systems [6–12]. The main conceptual difference between both problems lies in the maximization of the so-called declared social welfare by the ISO, which replaces the conventional minimization of the operating cost. Declared social welfare is a measure of social welfare that depends on the bids and offers submitted by market participants. When the demand is inelastic, the objective function only includes information on generation offers and the resulting problem becomes an offer cost minimization.

Under ideal conditions including perfect competition and convexity, the optimal market-clearing solution represents an equilibrium solution at which suppliers have no incentive to offer different from their production costs. Moreover, this equilibrium

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Nomenclature

Functions

$o^E_{jt}(\cdot)$	energy offer price function of unit j in period t

Indices

b	energy offer block index
j	generating unit index
l	time period index
t	time period index

Sets

B_j	index set of the energy blocks offered by unit j
J	index set of generating units
T	index set of time periods
Π_{jt}	feasibility set associated with the operation of unit j in period t

Constants

A_{jt}, B_{jt}, C_{jt}	coefficients of the quadratic energy offer cost function of unit j in period t
D_t	demand in period t
DT_j	minimum down time of unit j
F_j	number of periods during which unit j must be initially scheduled off due to its minimum down time constraint
L_j	number of periods during which unit j must be initially scheduled on due to its minimum up time constraint
n_{B_j}	number of energy blocks offered by unit j
n_J	number of generating units
n_T	number of time periods
O^E_{bjt}	price of the bth energy block offered by unit j in period t
O^{SU}_{jt}	start-up offer price of unit j in period t
$\overline{P}_{jt}$	upper bound for the power output of unit j in period t
$\underline{P}_{jt}$	lower bound for the power output of unit j in period t
RD_j	ramp-down rate of unit j
RU_j	ramp-up rate of unit j
S^0_j	number of periods during which unit j has been scheduled off prior to the first period of the time span (end of period 0)
SD_j	shut-down ramp rate of unit j
SU_j	start-up ramp rate of unit j
T_{bjt}	upper bound for the bth energy block offered by unit j in period t
UT_j	minimum up time of unit j
UT^0_j	number of periods during which unit j has been scheduled on prior to the first period of the time span (end of period 0)
V_{j0}	binary parameter that is equal to 1 if unit j is scheduled on prior to the first period of the time span (end of period 0), being 0 otherwise

Variables

p_{jt}	power output of unit j in period t
s_{jt}	payment for the start-up of unit j in period t
v_{jt}	binary variable that is equal to 1 if unit j is scheduled on in period t, being 0 otherwise
w_{bjt}	binary variable that is equal to 1 if the bth energy block offered by unit j is the last accepted block of its energy offer in period t, being 0 otherwise
λ_t	market-clearing price for energy in period t

maximizes the social welfare. Thus, the declared social welfare based on generation offers reflects the true social welfare, and hence, maximizing the declared social welfare is commonly accepted as the right goal in a market setting [1].

However, conventional market clearing presents several shortcomings [13,14]. In general, the assumption of perfect competition does not hold. As a result, generation offers may not reflect actual production costs and hence market-clearing solutions may be far from those maximizing the social welfare often to the detriment of consumers. This distortion may be stressed by the presence of non-convexities characterizing the operation of generating units [2,6,15] such as start-up offers, ramping rates, minimum generation limits, and minimum up and down times. Therefore, the fairness and economic efficiency of currently used market-clearing procedures may be questioned.

International experience in mitigating the effects of dishonest behavior and market power abuse includes attempts to improve the efficiency of offering in market-clearing procedures. Relevant examples can be found in several US electricity markets [16,17]. This practice however is not sufficient to completely disable the impact of market power. Therefore, structural changes in electricity markets are required, as suggested in [16].

Such need for renovation has motivated extensive research on alternative market-clearing procedures based on consumer payment minimization [14,18–30]. It is worth mentioning that this body of research relies on the pioneering work by Jacobs [13], who first proposed consumer payment minimization as an alternative goal in the auction design. These works have given rise to the recently coined notion of price-based market clearing [29], which embeds auction designs modeling the payment to market participants for the commodities provided such as energy [14,18–30], reserves [18,23,24,27], and reactive power [31]. Consumer payment minimization is a particular instance of this new class of auctions. Bearing in mind that actual production costs are private corporate information, consumer payment minimization has been proposed as a solution to the lack of incentives for suppliers to offer their actual costs in current auctions driven by the maximization of the declared social welfare. Thus, this alternative auction scheme may be considered as an instrument to protect consumers against the exercise of market power by suppliers via offering above their actual costs. However, consumer payment minimization faces obstacles for its practical implementation in current electricity markets.

First, consumer payment minimization raises concerns related to (i) the discrimination of generators in favor of consumers, (ii) the potential for gaming, and (iii) the investment cost recovery. Those issues regarding the short- and long-term economic efficiency of this auction design have resulted in an open debate that is beyond the scope of this paper. The interested reader is referred to [13,14,20,28] for further details on this discussion. Notwithstanding, it should be noted that those works rely on simplified models and approximate solution approaches. Therefore, no conclusive answer to the above concerns is available and hence new tools are required to either prove or disprove the economic efficiency of consumer payment minimization.

Moreover, alternative auction models based on consumer payment minimization [14,18–30] result in complex optimization problems as a consequence of their two main differences with respect to standard market-clearing procedures:

1. The objective function is modified to model the minimization of the consumer payment. Hence, the new objective function is explicitly dependent on the vector of market-clearing prices.