Electric Power Systems Research 163 (2018) 513–522

Contents lists available at ScienceDirect

Electric Power Systems Research

journal homepage: www.elsevier.com/locate/epsr

An integrated day-ahead market clearing model: Incorporating paradoxically rejected/accepted orders and a case study

Sinan Yörükoğlu[a,*], Zeynep Müge Avşar[b], Bora Kat[c]

[a] AF-Mercados EMI, Mustafa Kemal Mah. Dumlupınar Blv. No: 280, D Blok, No:3, 06510 Ankara, Turkey
[b] Department of Industrial Engineering, Middle East Technical University, Üniversiteler Mah. Dumlupınar Blv. No:1, 06800 Ankara, Turkey
[c] The Scientific and Technological Research Council of Turkey, Tunus Cd. No:80, 06100 Ankara, Turkey

ARTICLE INFO

Keywords:
OR in energy
Electricity day-ahead market
Combinatorial auctions
Social welfare
Non-linear programming

ABSTRACT

In the electricity day-ahead markets (DAMs), market participants place their orders in the form of desired/accepted price levels for the submitted quantities. The market operator evaluates these orders and announces the clearing quantities and market clearing prices (MCPs) within an hour. In this paper, a mathematical model is proposed for the exact solution of clearing electricity DAM with a focus on the current Turkish system. The model is a non-linear programming (NLP) problem that maximizes total social welfare and takes into account all types of orders that are submitted in the Turkish DAM. In order to ensure a feasible solution, the concept of paradoxically accepted/rejected orders is introduced. Two versions of the mathematical model are considered, allowing for one type of paradoxical processing in each version. For the computational experiments, a sample data set of 25 days, representing the conditions in the Turkish DAM, is generated and published on an open library. The model is solved to optimality within the practical time limitation of the market operator in all cases.

1. Introduction

Electricity can be traded in many different ways. In general, it can be accomplished either by long-term power purchase agreements (PPAs) or the spot market based on short-term auctions and energy exchange mechanisms. In any case, as noted in [1], the supply and demand must be always in balance as electricity is an intangible commodity that is difficult to store. As compared to the European markets, in Turkey greater amount of electricity is traded under long-term PPAs while the spot market, which is called by law the balancing and settlement market (BSM), has also a significant volume. The main platform to trade electricity in the BSM is the day-ahead market (DAM). It is reported in [2] that the share of DAM in total electricity trade carried out in Turkey was around 42% and 43% in 2016 and 2017, respectively.

This paper reviews the market clearing approaches in European markets with a specific focus on Turkey. European spot markets are organized as power exchange (PX) markets, which take place in the form of double auctions (double blind auctions), meaning that there are several bidders on both buyer and seller sides for the same product or commodity [3]. The Central Western European (CWE) region couples the PX markets of five countries (Belgium, France, Germany, Luxembourg and the Netherlands) and clears those markets by making use of a Branch-and-Bound based algorithm called COSMOS [4]. Similarly, the Scandinavian and Baltic countries (Finland, Denmark, Sweden, Norway, Estonia and Lithuania) used to be coupled by Nord Pool Spot coupling system called SESAM [5]. The EPEXSpot [6] integrated the PX markets of the United Kingdom, Austria and Switzerland with the CWE countries. Finally, seven European PX markets have been merged by the system called "Pan-European Hybrid Electricity Market Integration Algorithm (EUPHEMIA)" [7], which covers 23 individual countries.[1]

- Before EUPHEMIA, for instance, the clearing process in the Iberian peninsula (Spain and Portugal) consisted of several stages implemented by OMEL [8]. These stages are the calculation of a provisional clearing price involving only simple bids (hourly bids having only a price and amount of energy), and step by step, iterative inclusion of complex bids,[2] such as Load Gradient, Indivisibility, Minimum Income and Scheduled Shutdown bids.
- The COSMOS algorithm [4] used in CWE region includes single

* Corresponding author.
E-mail addresses: syyorukoglu@gmail.com (S. Yörükoğlu), mavsar@metu.edu.tr (Z.M. Avşar), borakat@gmail.com (B. Kat).

[1] Austria, Belgium, Czech Republic, Denmark, Estonia, Finland, France, Germany, Hungary, Italy, Latvia, Lithuania, Luxembourg, the Netherlands, Norway, Poland, Portugal, Romania, Slovakia, Slovenia, Spain, Sweden and UK.

[2] Complex bid is a special type of simple bids in the sales direction that contain various "complex" conditions, creating additional restrictions on hourly bids.

https://doi.org/10.1016/j.epsr.2018.07.007
Received 21 March 2018; Received in revised form 13 June 2018; Accepted 6 July 2018
Available online 02 August 2018

orders that are essentially the same as the simple bids in OMEL, as well as block orders that have "fill-or-kill" property. The algorithm first solves the market clearing problem by maximizing social welfare without the fill-or-kill conditions. Then, fill-or-kill constraints are added to the branch-and-bound algorithm and a final solution is found.

- As the European market integration model, EUPHEMIA involves bid types from both OMEL and CWE regions [7]; namely, single bids (hourly orders), complex orders (only Minimum Income Condition and Load Gradient), block orders (including linked and flexible orders), merit orders and PUN (Prezzo Unico Nazionale) orders.[3] The algorithm consists of one master problem that maximizes welfare and three interdependent sub-problems. The merit and PUN orders are not enforced in the master problem. The first sub-problem is the price-determination sub-problem and it aims to find a market clearing price (MCP) for each bidding area. Next, the PUN search sub-problem tries to find valid PUN volumes and prices for each hour of the day. Finally, volume indeterminacy sub-problem focuses on the price-taking orders, merit order numbers and maximizes the traded volume.

In addition to the above algorithms, there are a few non-commercial applications on electricity DAM clearing. Martin et al. [9] solve the European DAM clearing problem in two steps considering a quadratic model that maximizes welfare, and a linear pricing problem. Consumer and producer surpluses in the welfare model are calculated as market participants' marginal willingness to pay. As the original welfare maximization model is hard to solve in a limited time, they propose a heuristic algorithm that first relaxes price conditions of block and flexible orders and later introduce cuts for those orders that do not satisfy the conditions. Biskas et al. [10] formulate the European DAM as both Power Pool and PX by minimizing the difference between total cost and total utility of every market participant to determine MCP. In the second part [11], they use an iterative algorithm for evaluation of block and flexible orders compared to the obtained MCP and acceptance decisions are finalized. For the Turkish market, Derinkuyu [1] proposes a mixed integer programming (MIP) model that minimizes total prices in a day. In order to decrease the solution times, aggregation of hourly orders (problem size reduction), lower and upper bounds for MCPs (variable elimination), and a heuristic for initial solution are proposed.

There are also studies in the literature, for instance [12–14], considering either jointly (with active power market) or independently clearing the reactive power market. What these studies have in common, also with others such as [9,10,15,16], is that power flow between network lines/buses or bidding areas, and transmission capacities at interconnection points or nodes are included in the market clearing models. These constraints are needed when the market under consideration consists of multiple regions or bidding areas as in the case of European market. In other words, these models aim at "physical clearing of DAM" from the transmission system operators' point of view. In this paper, we focus on "financial clearing of DAM" where the bids/orders of market participants are of concern. Studying the Turkish electricity market that is operated as a single bidding area allows us to leave out physical power flow balance and transmission capacity constraints from our model, although we propose a conceptual model for a general multi-region case.

Another relevant line of study regarding DAM is the optimization of bidding strategy of electricity generators. This problem generally falls into the category of Unit Commitment and Economic Dispatch problems (see [17] for definitions). Different solution approaches have been adopted for this problem, including but not limited to fuzzy methods and evolutionary algorithms as in [18–20], scenario based approach in [21], stochastic quadratic modeling and Karush–Kuhn–Tucker (KKT) solutions in [22], using polyhedral uncertainty sets for model parameters in [23], and cutting plane algorithms in [24]. In a different approach used in their two-part articles, Aussel, Bendotti and Pištěk [25,26] model electricity markets as multi-leader-common-follower games, and show that Nash equilibria exist and find the best-response of electricity generators. In most of these (and other) papers, ramp-up and ramp-down costs, rates and/or limits for generators, including generation and load uncertainties, are taken into consideration. However, these constraints are not included in our market clearing model, as they are incorporated into the bids/orders of generators as part of their bid/order prices of—especially—block orders (as also emphasized in [16,27]). In other words, ignoring explicit representation of these constraints does not mean that they are not taken into account. This approach is in line with the the argument stated in [17], i.e., "European day-ahead markets … can be seen to some extent as a mean to solve a Unit Commitment and Economic Dispatch problem where characteristics are given to Market Operators (coupled power exchanges) in charge of computing the solution, and determining the corresponding market prices". Moreover, it is straightforward to add the electricity network and related constraints including power flow equations to our model as side constraints. However, we wanted to keep our model as simple as possible to focus on handling paradoxically accepted/rejected orders and demonstrate the success of the proposed model sticking to actual practice in Turkish power market and other markets which employ the same practice.

The Turkish DAM is operated by Energy Exchange Istanbul (EXIST-EPIAS), who is referred to as the market operator. Main purpose of the DAM is to clear the imbalances in the network by allowing hourly settlement of electricity exchanges. The market participants submit their bids for each hour of the next day.

The bids submitted in the Turkish Electricity DAM are allowed to have three different structures; namely hourly, block and flexible bids [28]. These bids are evaluated simultaneously by the recently developed optimization tool, maximizing the total producer and consumer surplus [29]. The operation of the Turkish DAM, bidding structure and their evaluation are described in detail in Section 2.

Below, our contribution in this article is summarized.

- Maximization of social welfare in the objective function: While researchers like [4,9], who also used welfare maximization, solve their models by applying a heuristic, we directly solve our model to optimality in relatively short times. With the data on hand, the optimality of the solutions (when a solution is found) is ensured by the version of the solver we use, i.e., CPLEX 12.6.2 in GAMS, which is able to solve non-convex quadratic programming (QP) problems to—global—optimality when the solution parameters are set properly [30,31].
- Involvement of paradoxically rejected and paradoxically accepted orders: We propose a novel approach to incorporate and account for the paradoxically processed orders. In other studies, for instance, all [32] or negative-welfare-incurring [15] paradoxically processed orders are handled in an iterative way and aimed to be completely eliminated from the market solution. The mathematical model proposed in this paper does not require a separate—iterative—procedure or removal of paradoxically accepted or rejected orders. Instead, our model explicitly designates these orders with a single run (solution). Only in [27], the number of paradoxically rejected block orders are considered and reported in a relatively limited way by maximizing what is called "trade efficiency (gains from trade)". On the other hand, in [1,10] the authors do not mention any paradoxical orders, whereas paradoxically rejected orders are included implicitly in [4,9], and the opportunity costs of

[3] Merit order is an individual step order associated with a so-called merit order number. PUN order is a special kind of merit order. Detailed description of all order types can be found in the public description document of EUPHEMIA.