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A new approach to electricity market clearing with uniform purchase price and curtailable block orders

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HIGHLIGHTS

- Electricity market clearing with curtailable block orders and uniform purchase price.
- Equivalent reformulation of the uniform purchase price.
- Exact and heuristic-free model cast as a mixed-integer linear program.
- Python implementation freely available in a public repository.

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ABSTRACT

The European market clearing problem is characterized by a set of heterogeneous orders and rules that force the implementation of heuristic and iterative solving methods. In particular, curtailable block orders and the uniform purchase price pose serious difficulties. A block order spans over multiple hours, and can be either fully accepted or fully rejected. The uniform purchase price prescribes that all consumers pay a common price in all the zones, while producers receive zonal prices, which can differ from one zone to another.

The market clearing problem in the presence of both the uniform purchase price and block orders is a major open issue in the European context. The uniform purchase price scheme leads to a non-linear optimization problem involving both primal and dual variables, whereas block orders introduce multi-temporal constraints and binary variables into the problem. As a consequence, the market clearing problem in the presence of both block orders and the uniform purchase price can be regarded as a non-linear integer programming problem involving both primal and dual variables with complementary and multi-temporal constraints.

The aim of this paper is to present a non-iterative and heuristic-free approach for solving the market clearing problem in the presence of both curtailable block orders and the uniform purchase price scheme. The solution is exact, with no approximation up to the level of resolution of current market data. By resorting to an equivalent uniform purchase price formulation, the proposed approach results in a mixed-integer linear program, which is built starting from a non-linear integer bilevel programming problem. Numerical results using real market data are reported to show the effectiveness of the proposed approach. The model has been implemented in Python, and the code is freely available on a public repository.

1. Introduction

Electricity markets are experiencing significant changes due to different factors, as the modification of generation mix [1], the increasing presence of demand response [2] and energy storage systems [3], the growth of renewable energy [4], the request for both flexibility [5,6] and security of supply [7], and the associated adjustment in power networks [8]. These changes affected also the European markets. In particular, the current day-ahead European electricity market is the result of a merging process that took place during the last three decades and involved all the main European countries [9], and it should lead to significant social welfare improvements [10]. However, the complete integration involves several difficulties both in terms of design [11], and interaction between different markets [12]. In particular, the lack

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Nomenclature

A. Sets and indices

- i — index of market zones, $i \in \mathscr{Z}$.
- $\mathscr{K}_{ti}^{\pi}$ — set of consumers paying the UPP π_t in zone $i \in \mathscr{Z}$, with $t \in \mathscr{T}$.
- $\mathscr{K}_{t}^{\pi}$ — set of all consumers paying the UPP, i.e., $\mathscr{K}_t^{\pi} = \cup_i \mathscr{K}_{ti}^{\pi}$, with $t \in \mathscr{T}$.
- $\mathscr{K}_{ti}^{\zeta}$ — set of consumers paying the zonal price ζ_{ti} in zone $i \in \mathscr{Z}$, with $t \in \mathscr{T}$.
- $\mathscr{K}_{t}^{\zeta}$ — set of all consumers paying zonal prices, i.e., $\mathscr{K}_t^{\zeta} = \cup_i \mathscr{K}_{ti}^{\zeta}$, with $t \in \mathscr{T}$.
- $\mathscr{K}_{ti}$ — set of all consumers in zone $i \in \mathscr{Z}$, i.e., $\mathscr{K}_{ti} = \mathscr{K}_{ti}^{\pi} \cup \mathscr{K}_{ti}^{\zeta}$, with $t \in \mathscr{T}$.
- $\mathscr{K}_{t}$ — set of all consumers, i.e., $\mathscr{K}_t = \cup_i \mathscr{K}_{ti}$, with $t \in \mathscr{T}$.
- $\mathscr{P}_{ti}$ — set of producers submitting simple stepwise order in zone $i \in \mathscr{Z}$, with $t \in \mathscr{T}$.
- $\mathscr{P}_{t}$ — set of all producers submitting simple stepwise order, i.e., $\mathscr{P}_t = \cup_i \mathscr{P}_{ti}$, $t \in \mathscr{T}$.
- $\mathscr{P}_{i}^{B}$ — set of producers submitting curtailable profile block orders in zone $i \in \mathscr{Z}$.
- $\mathscr{P}^{B}$ — set of all producers submitting curtailable profile block orders, i.e., $\mathscr{P}^B = \cup_i \mathscr{P}_i^B$.
- $\mathscr{T}$ — set of the 24 daily hours.
- $\mathscr{T}_p$ — set of block order p timespan, with $p \in \mathscr{P}^B$, and $\mathscr{T}_p \subseteq \mathscr{T}$.
- $\mathscr{Z}^{\pi}$ — set of zones enforcing the UPP π_t.
- $\mathscr{Z}^{\zeta}$ — set of zones without the UPP, all consumers pay zonal prices ζ_{ti}.
- $\mathscr{Z}$ — set of all zones, $\mathscr{Z} = \mathscr{Z}^{\pi} \cup \mathscr{Z}^{\zeta}$.

B. Constants

- D_{tk}^{max} — maximum hourly quantity demanded by consumer $k \in \mathscr{K}_t$ at time $t \in \mathscr{T}$.
- F_{tij}^{max} — maximum flow capacity from zone i to zone j with $t \in \mathscr{T}$.
- $M^{(\cdot)}$ — M^{π}, M_p^B, M_{tij}^F, and M_{th}^D are big-M parameters.
- O_{tk}^{m} — merit order for consumer $k \in \mathscr{K}_t^{\pi}$, lower values mean higher priority.
- P_{tk}^{d} — hourly order price submitted by consumer $k \in \mathscr{K}_t$ with $t \in \mathscr{T}$.
- P_{tp}^{s} — hourly order price submitted by producer $p \in \mathscr{P}_t$ with $t \in \mathscr{T}$.
- P_{p}^{B} — block order price submitted by producer $p \in \mathscr{P}^B$.
- R_{p}^{min} — minimum acceptance ratio for curtailable block order with $p \in \mathscr{P}^B$.
- S_{tp}^{max} — maximum hourly quantity offered by producer $p \in \mathscr{P}_t$ at time $t \in \mathscr{T}$.
- $S_{tp}^{B,max}$ — profile block order maximum hourly quantity offered by producer $p \in \mathscr{P}^B$ with $t \in \mathscr{T}_p$.

C. Variables

- b_{tji} — binary variable used in the binary expansion to convert a positive integer number in binary form, where $i \in \mathscr{Z}^{\pi}$, $t \in \mathscr{T}$, and $j \in \{0, \ldots\}$.
- d_{tk}^{ζ} — executed demand quantity for consumer $k \in \mathscr{K}_t^{\zeta}$, with $t \in \mathscr{T}$.
- d_{tk}^{w} — executed demand quantity for consumer $k \in \mathscr{K}_t^{\pi}$ if $u_{tk}^{w} = 1$, with $t \in \mathscr{T}$.
- d_{tk}^{d} — executed demand quantity for consumer $k \in \mathscr{K}_t^{\pi}$ if $u_{tk}^{d} = 1$, with $t \in \mathscr{T}$.
- d_{tk}^{π} — executed demand quantity for consumer $k \in \mathscr{K}_t^{\pi}$, where $d_{tk}^{\pi} = u_{tk}^{g} D_{tk}^{max} + d_{tk}^{w} + d_{tk}^{d}$, with $k \in \mathscr{K}_t^{\pi}$ and $t \in \mathscr{T}$.
- f_{tij} — flow from zone i to zone j with $t \in \mathscr{T}$.
- r_p — block order acceptance ratio with $p \in \mathscr{P}^B$.
- s_{tp} — executed supply quantity for producer $p \in \mathscr{P}_t$, with $t \in \mathscr{T}$.
- u_{tij}^{f} — binary variable with i, $j \in \mathscr{Z}^{\pi}$ and $t \in \mathscr{T}$, where $u_{tij}^{f} = 1$ if and only if the transmission line from i to j is congested, i.e., $f_{tij} = F_{tij}^{max}$.
- u_{p}^{B} — binary variable representing the block order acceptance status with $p \in \mathscr{P}^B$, where $u_p^B = 1$ means accepted, and $u_p^B = 0$ rejected.
- u_{tk}^{g} — binary variable with $k \in \mathscr{K}_t^{\pi}$ and $t \in \mathscr{T}$, where $u_{tk}^{g} = 1 \Leftrightarrow P_{tk}^{d} > \pi$, and zero otherwise.
- u_{tk}^{e} — binary variable with $k \in \mathscr{K}_t^{\pi}$ and $t \in \mathscr{T}$, where if $u_{tk}^{e} = 1$ then $P_{tk}^{d} = \pi$.
- u_{tk}^{w} — binary variable with $k \in \mathscr{K}_t^{\pi}$ and $t \in \mathscr{T}$, where if $u_{tk}^{w} = 1$ then the demand order is at-the-money and it is partially cleared according to a social welfare approach.
- u_{tk}^{d} — binary variable with $k \in \mathscr{K}_t^{\pi}$ and $t \in \mathscr{T}$, where if $u_{tk}^{d} = 1$ then the demand order is at-the-money and it is partially cleared according to an economic dispatch approach.
- δ_{tij}^{max} — dual variable of constraint $f_{tij} \leqslant F_{tij}^{max}$.
- ζ_{ti} — zonal price in zone $i \in \mathscr{Z}$ with $t \in \mathscr{T}$.
- η_{tij} — dual variable of constraint $f_{tij} + f_{tji} = 0$.
- κ_t — error tolerance in the uniform purchase price definition, currently $\kappa_t \in [-1;5]$.
- φ_{tk}^{ζ} — dual variable of constraint $d_{tk}^{\zeta} \leqslant D_{tk}^{max}$.
- φ_{tk}^{w} — dual variable of constraint $d_{tk}^{w} \leqslant D_{tk}^{max} u_{tk}^{w}$.
- $\varphi_{tk}^{w,lo}$ — dual variable of constraint $d_{tk}^{w} \geqslant 0$.
- φ_{tp}^{s} — dual variable of constraint $s_{tp} \leqslant S_{tp}^{max}$.
- $\varphi_{p}^{B,max}$ — dual variable of constraint $r_p \leqslant u_p^B$.
- $\varphi_{p}^{B,min}$ — dual variable of constraint $r_p \geqslant u_p^B R_p^{min}$.
- π_t — uniform purchase price at time $t \in \mathscr{T}$.

D. Auxiliary variables

- $y_{tk}^{g\pi}$ — auxiliary variable, it replaces the product $u_{tk}^{g}\pi$.
- $y_{tki}^{g\zeta}$ — auxiliary variable, it replaces the product $u_{tk}^{g}\zeta_{ti}$.
- $y_{tk}^{e\pi}$ — auxiliary variable, it replaces the product $u_{tk}^{e}\pi_t$.
- $y_{tk}^{w\varphi}$ — auxiliary variable, it replaces the product $u_{tk}^{w}\varphi_{tk}^{w}$.
- $y_{p}^{B\varphi,max}$ — auxiliary variable, it replaces the product $u_p^B \varphi_p^{B,max}$.
- $y_{p}^{B\varphi,min}$ — auxiliary variable, it replaces the product $u_p^B \varphi_p^{B,min}$.
- $y_{tij}^{b\zeta}$ — auxiliary variable, it replaces the product $b_{tji}\zeta_{ti}$.

of an original common design, leads to a European day-ahead electricity market that is characterized by heterogeneous orders (e.g., stepwise orders, piecewise linear orders, simple and linked block orders [13]), and rules (e.g., minimum income condition [14], uniform purchase price [15]), which cannot be easily harmonized. As a consequence, the European market clearing algorithm [13] deals with a wide variety of issues, due to, for example, the complexity of both the clearing rules and the orders involved, their heterogeneous nature, and the increasing number of orders currently submitted to the market, which forced the implementation of heuristics and iterative solving methods. One of the most challenging problem is the simultaneous presence of block orders and the uniform purchase pricing scheme. Block orders are present in the central and northern European countries [16,17], whereas the uniform purchase price (UPP) is implemented into the Italian market [15] with the name of *Prezzo Unico Nazionale* (PUN).

1.1. The UPP scheme

The UPP scheme requires that all consumers pay a unique price, termed the UPP, in all the zones, while producers receive zonal prices,