European day-ahead electricity market coupling: Discussion, modeling, and case study

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A B S T R A C T

Currently, the integration of European Electricity Market (EEM) has led to a single European Day-Ahead Market (DAM) with multiple-areas considered as bidding zones. In the near future, the EEM will spread to the Intra-day and Balancing market. To operate the DAM, a market clearing tool (algorithm) has been developed by market operators. The development of this algorithm corresponds to three primary principles: (i) one single framework, (ii) robust operation, and (iii) individual accountability. However, this algorithm is not available to the research community. In this paper, the authors develop a complete European DAM model in General Algebraic Modelling System (GAMS), formulating it as a Mixed Integer Quadratic Constraint Problem (MIQCP) and iterative procedure, to mitigate the non-convexity of electricity prices across Europe due to the “fill or kill” condition of block, complex and Prezzo Unico Nazionale (PUN) orders. Eventually, two case studies reflecting the current European DAM evaluated the model, aiming to confirm its robustness and reliability.

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1. Introduction

In Europe, the spot market is operated by the Power Exchange (PX), while the Transmission System Operator (TSO) provides network boundary conditions, within which the system feasibility and security is guaranteed. Some PXs have split their market into several bidding zones based on national borders or network bottlenecks. For instance, the EPEX Spot has three bidding areas (France, Germany/Austria, and Switzerland) [1], while the GME (Italy) has more than 20 bidding areas [2].

The idea of a single energy market in Europe has been proposed in the Internal Energy Market (IEM) [3] project for the last two decades, to achieve three primary objectives: (i) affordable energy, (ii) competitive prices and (iii) environmental sustainability. In the first step of IEM, the Price Coupling of Regions project (PCR) has entirely coupled the DAMs of GME, EPEX Spot (only France, Germany and Austria in PCR), APX (UK and Netherlands), Belpex (Belgium), Nord Pool Spot (Scandinavian countries), OMIE (Spain and Portugal), and OTE (Czech Republic). The main PCR benefits [4,5] are (i) improving the market liquidity; (ii) guaranteeing the overall welfare, and (iii) implicit allocation management.

The PCR focuses on the development of a single market clearing algorithm based on the SESAM [6] and COSMOS [7], to calculate energy distribution and electricity price across Europe. The algorithm is named the Pan-European Hybrid Electricity Market Integration Algorithm (EUPHEMIA) [8], and its goals are to cover all specified conditions of every partial PX simultaneously and give solution within a reasonable time frame. Obviously, the combination of PXs could be risky if one looks at the coherence of their market rules. In details, one of the major problems is the non-convexity of electricity price due to the “fill-or-kill” condition of block, MIC and PUN orders. Moreover, the collaboration of the allocation methodologies (Available Transmission Capacity (ATC) and Flow-Based (FB) models), the false rejected block orders, and the decreasing of the fairness for market players because of the short computing time also put stress on EUPHEMIA.

1.1. Structure of the European day-ahead electricity market

1.1.1. Market orders

Paper [8] presents the structure and acceptance rule of all type of orders, including aggregated hourly, complex, block, and PUN orders [9]. Papers [10,11] show the main characteristics of the DAM in Europe. All the orders in the DAM are located in a Share Order Book (SOB) which is used as input data for the market clearing algorithm. In this subparagraph, these orders and related acceptance rules are briefly described.
Nomenclature

Acronyms

EM Internal Energy Market
EEM European Electricity Market
DAM Day-Ahead Market
PCR Price Coupling of Regions project
EUPHEMIA Pan-European Hybrid Electricity Market Integration Algorithm
CWE Central Western Europe
GAMS General Algebraic Modelling System
PX Power Exchange
TSO Transmission System Operator
PUN Prezzo Unico Nazionale
LGC Load Gradient Condition
MIC Minimum Income Condition
SSC Schedule Stop Condition
ATC Available Transmission Capacity
FB Flow-Based
SOB Share Order Book
PAB Paradoxically Accepted Block order
PRB Paradoxically Rejected Block order
PAMIC Paradoxically Accepted MIC order
PRMIC Paradoxically Rejected MIC order
SW Social Welfare
RAM Remain Available Margin
PTDFs Power Transfer Distribution Factors
SWMP Social Welfare Maximization Problem
PAMIC-SP Paradoxically Accepted MIC Sub-Problem
PAB-SP Paradoxically Accepted Block Sub-Problem
PUN-SP PUN search Sub-Problem
PRMIC-SP Paradoxically Rejected MIC Sub-Problem
PRB-SP Paradoxically Rejected Block Sub-Problem

Sets

t ∈ T set of dispatch periods in one day
a ∈ A set of bidding areas

Sets of interconnectors
cb ∈ CB set of all critical branches
l ∈ Br_{fa,ta} set of interconnectors between areas fa ∈ A and area ta ∈ A. The power flow is positively defined from fa to ta
l ∈ Br_{fa,ta}^{DC} subset of DC interconnectors, including the ATC region (Br_{fa,ta}^{ATC,DC}), and the FB region (Br_{fa,ta}^{FB,DC}), Br_{fa,ta}^{ATC+FB,DC} = Br_{fa,ta}^{ATC,DC} \cup Br_{fa,ta}^{FB,DC}, and the DC connections between ATC and FB region (Br_{fa,ta}^{ATC,FB,DC}), Br_{fa,ta}^{DC} = Br_{fa,ta}^{ATC+FB,DC} \cup Br_{fa,ta}^{ATC,FB,DC}, Br_{fa,ta}^{DC} \subseteq Br_{fa,ta}

l ∈ Br_{fa,ta}^{AC} subset of AC interconnectors, including the ATC region (Br_{fa,ta}^{ATC,AC}), and the FB region (Br_{fa,ta}^{FB,AC}), Br_{fa,ta}^{ATC+FB,AC} = Br_{fa,ta}^{ATC,AC} \cup Br_{fa,ta}^{FB,AC}, and the AC connections between ATC and FB region (Br_{fa,ta}^{ATC,FB,AC}), Br_{fa,ta}^{AC} = Br_{fa,ta}^{ATC+FB,AC} \cup Br_{fa,ta}^{ATC,FB,AC}, Br_{fa,ta}^{AC} \subseteq Br_{fa,ta}
l ∈ Br_{fa,ta}^{AC} subset of interconnectors in ATC region, where Br_{fa,ta}^{AC} = Br_{fa,ta}^{ATC,AC} \cup Br_{fa,ta}^{ATC,DC}, Br_{fa,ta}^{AC} \subseteq Br_{fa,ta}
l ∈ Br_{fa,ta}^{FB} subset of interconnectors in FB region, where Br_{fa,ta}^{FB} = Br_{fa,ta}^{FB} \cap Br_{fa,ta}^{DC}, Br_{fa,ta}^{FB} \subseteq Br_{fa,ta}
l ∈ IS set of interconnectors that are subject to the same constraint
Is ∈ LS set of all Is
l ∈ Br_{fa,ta}^{HR} subset of interconnectors that subject to the hourly ramping constraint, Br_{fa,ta}^{HR} \subseteq Br_{fa,ta}

Sets of orders

s ∈ Sa set of hourly step orders submitted at bidding area a, including stepwise ss ∈ Ssa and piecewise hourly order sp ∈ Sp, where Ssa = Ssa ∪ Sp

ss ∈ Ssa \cup Sp set of PUN orders, Ssa \cup Sp \subseteq Ssa

b ∈ Ba set of block orders submitted at bidding area a

pb ∈ b set of small block orders which define block order b
eg ∈ Ega set of exclusive group orders including many regular block orders submitted at bidding area a

lb ∈ LBa set of link block orders submitted at bidding area a
fh ∈ FHa set of flexible hourly orders submitted at bidding area a

p ∈ Pa set of producers submitted at bidding area a, it can be unit or portfolio

p ∈ LGCp set of producers p subject to LGC, where LGCp ⊆ Pa

p ∈ MICp \setminus \{p\} set of producers \setminus \{p\} subject to MIC, where MICp \setminus \{p\} \subseteq Pa

p ∈ SSCa set of producers p subject to SSC, where SSCa \subseteq Pa

Parameters

Pt, Qt \in \mathbb{R}+ price and quantity of step hourly order ss in period t, in €/MWh and MWh, respectively

P0/1t, Qopp price and quantity of piecewise hourly order sp, in period t, in €/MWh and MWh, respectively

Pb, Qpb price and quantity of small block order pb belong to block order b in period t, in €/MWh and MWh, respectively

Pfh, Qfh \in \mathbb{R}+ price and quantity of flexible block order fh in period t, in €/MWh and MWh, respectively

The value of submitted quantity is positive for demand side and negative for supply side

Tpb, Tpb starting (ending) dispatch period of small block orders pb

Ufb, Ufb starting (ending) unit steps of small block orders pb.

Here, its value receives 1 if t ≥ Tpb and receives 0 if t < Tpb, ∀t ∈ T

R_{b,p}^{min} minimum acceptance ratio of block order b in p.u.;

where: 0 ≤ R_{b,p}^{min} ≤ 1 for profile block order and R_{b,p}^{min} = 1 for regular block order

IM_{b}^{lb} incidence matrix relating the link block order to its parent. Thus, the km-th element of IM_{b}^{lb} is 1 if k ∈ b block order is the parent of m ∈ lb link block order, otherwise is null

IGp(Dp) maximum increase (decrease) gradient of producer p in MWh, where IGp \in \mathbb{R}^+, Dp \in \mathbb{R}^-, ∀p ∈ LGCp

FTp(VTp) fixed term (Variable term) of the MIC of producer p in €/MWh, ∀p ∈ MICp

Ymicp binary parameter indicating if the producer p subjects to MIC is located in share order book or not (1 is located and 0 is not)

Yssc_{sa} status of hourly stepwise orders of producer subject to SSC in period t; it is equal to 1 for the first hourly sub-order in the first three periods, and 0 for the rest

Br_{l,t}^{max/ \min} limit capacity of inter-connector l in period t in MWh, where Br_{l,t}^{max/ \min} \in \mathbb{R}^+, Br_{l,t}^{max/ \min} \in \mathbb{R}^-

Inp_{l/b/a} initial power of the interconnector l, the line set l, the area a in the last hour of previous day in MWh, respectively

Inp_{a}^d the net position of area a in previous day in MW
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