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# Incorporating unit commitment aspects to the European electricity markets algorithm: An optimization model for the joint clearing of energy and reserve markets

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## HIGHLIGHTS

- An MILP model for the extension of EUPHEMIA hourly offers module is presented.
- Power reserves market is jointly cleared with energy market.
- Minimum income condition is extended to include also welfare from reserve market.
- Intra-hourly ramping constraints guarantee system's flexibility capability.
- Strategy, market structure, and power trading affect techno-economic decisions.

## ARTICLE INFO

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## ABSTRACT

The European electricity markets' integration aims at the market coupling among interconnected power systems and the enhancement of market competitive forces. This process is facilitated by the adoption of a common clearing algorithm among European power exchanges, entitled EUPHEMIA (Pan-European Hybrid Electricity Market Integration Algorithm), which however lacks to capture critical technical aspects of power systems, as done by the unit commitment problem including start-up and shut-down decisions, time constraints (minimum on- and off-times), as well as the consideration of ancillary services. This paper presents an optimization-based framework for the optimal joint energy and reserves market clearing algorithm, further utilizing the hourly offers module of the EUPHEMIA algorithm. In particular, through the formulation of a mixed integer linear programming (MILP) model and employing an iterative approach, it determines the optimal energy and reserves mix, the resulting market clearing prices, and it calculates the welfares of the market participants. The model incorporates intra-hourly power reserve constraints, as well as introduces new market products such as the option of forming linked groups of power units, aiming at supplying additional flexibility in the decision-making of the market participants. The model applicability has been assessed in the Greek power system and its interconnections with neighboring power systems in Southeast Europe. The proposed optimization framework can provide useful insights on the determination of the optimal generation and interconnection portfolios that address the new market-based operational challenges of contemporary power systems subject to technical and economic constraints.

## 1. Introduction

Global transition towards low-carbon power systems constitutes a declared target at an international level, with the objective of mitigating average global temperature increase to "well below 2 °C" in the current century, in comparison with pre-industrial levels. Since 1990,

*Abbreviations:* EUPHEMIA, Pan-European Hybrid Electricity Market Integration Algorithm; LIG, lignite-fired units; LP, Linear Programming; MCP, Mixed Complementarity Problem; MILP, Mixed Integer Linear Programming; MIP, Mixed Integer Programming; MIQCP, Mix Integer Quadratic Constraint Problem; NGCC, natural gas-fired combined cycle units; NGGT, natural gas-fired open cycle units; PCR, Price Coupling of Regions; PUN, Prezzo Unico Nazionale; SEM, Single Electricity Market

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## Nomenclature

*Sets*

$f^{ht}$ set of operational blocks $f$ of each hydrothermal unit $ht$, representing a specific price-quantity pair
$f^{dm}$ set of blocks $f$ of each load bid $dm$, representing a specific price-quantity pair
$f^{in}$ set of operational blocks $f$ of each interconnection $in$, representing a specific price-quantity pair
$h$ set of hydroelectric units
$ht$ set of hydrothermal units
$a$ set of supply entities, including thermal, hydroelectric, and renewable units
$dm$ set of load entities
$dt$ set of representative days
$in$ set of interconnections of the studied power system
$res$ set of renewable units
$t$ set of time periods
$th$ set of thermal units

*Parameters*

$B^{prd}_{ht,t,f^{ht},dt}$ quantity of each block $f^{ht}$ of the energy supply function of each unit $ht$ in each time period $t$ and representative day $dt$ (MW)
$B^{dem}_{dm,t,f^{dm},dt}$ quantity of each block $f^{dm}$ of the load bid function of each load entity $dm$ in each time period $t$ and representative day $dt$ (MW)
$B^{exp}_{in,t,f^{in},dt}$ quantity of each block $f^{in}$ of the exported energy function of each interconnection $in$ in each time period $t$ and representative day $dt$ (MW)
$B^{imp}_{in,t,f^{in},dt}$ quantity of each block $f^{in}$ of the energy supply function of each interconnection $in$ (imports) in each time period $t$ and representative day $dt$ (MW)
$C^{prd}_{ht,t,f^{ht},dt}$ energy supply cost function of each unit $ht$ in each operational block $f^{ht}$, time period $t$ and representative day $dt$ (€/MW)
$C^{2-}_{ht,t,dt}$ secondary-down reserve provision cost function of each unit $ht$ in each time period $t$ and representative day $dt$ (€/MW)
$C^{2+}_{ht,t,dt}$ secondary-up reserve provision cost function of each unit $ht$ in each time period $t$ and representative day $dt$ (€/MW)
$C^{3ns}_{ht,t,dt}$ non-spinning (offline) tertiary-up reserve provision cost function of each unit $ht$ in each time period $t$ and representative day $dt$ (€/MW)
$C^{3s-}_{ht,t,dt}$ spinning tertiary-down reserve provision cost function of each unit $ht$ in each time period $t$ and representative day $dt$ (€/MW)
$C^{3s+}_{ht,t,dt}$ spinning tertiary-up reserve provision cost function of each unit $ht$ in each time period $t$ and representative day $dt$ (€/MW)
$C^{dem}_{dm,t,f^{dm},dt}$ load bid cost function of each load entity $dm$ in each segment $f^{dm}$, time period $t$ and representative day $dt$ (€/MW)
$C^{exp}_{in,t,f^{in},dt}$ exported energy cost function of each interconnection $in$ (exports) in each operational block $f^{in}$, time period $t$ and representative day $dt$ (€/MW)
$C^{imp}_{in,t,f^{in},dt}$ energy supply cost function of each interconnection $in$ (imports) in each operational block $f^{in}$, time period $t$ and representative day $dt$ (€/MW)
$C^{var}_{th,t,dt}$ minimum average variable cost of each thermal unit $th$ in each time period $t$ and representative day $dt$ (€/MW)
$C^{sd}_{th}$ shut-down cost of each thermal unit $th$ (€)
$DT_{th}$ minimum down-time of each unit $th$ (h)
$INT^{exp}_{in,t,dt}$ capacity of each interconnection $in$ (exports) in each time period $t$ and representative day $dt$ (MW)
$INT^{imp}_{in,t,dt}$ capacity of each interconnection $in$ (imports) in each time period $t$ and representative day $dt$ (MW)
$LG^{dn}_{ht,t,dt}$ maximum decrease gradient of each $ht$ in each time period $t$ and representative day $dt$ imposed by a Load Gradient Order (MW/min)
$LG^{up}_{ht,t,dt}$ maximum increase gradient of each unit $ht$ in each time period $t$ and representative day $dt$ imposed by a Load Gradient Order (MW/min)
$LNK_{th,th',dt}$ linkage status among thermal units $th$ (parent-unit) and $th'$ (child-unit) in each representative day $dt$ (1, if there is linkage, and 0, otherwise)
$L_{a,t,dt}/L_{in,t,dt}$ power injection losses coefficient of each supply entity $a$ or interconnection $in$ (imports) in each time period $t$ and representative day $dt$ (per unit)
$M_{a,t,dt}$ non-priced mandatory energy production of each unit $a$ in each time period $t$ and representative day $dt$ (MW)
$N^{sec}$ percentage of secondary reserve requirements on the energy demand requirements (%)
$N^{ter}$ percentage of tertiary reserve requirements on the energy demand requirements (%)
$P^{max}_{ht,t,dt}$ available technical maximum of each unit $ht$ in each time period $t$ and representative day $dt$ (MW)
$P^{min}_{ht,t,dt}$ technical minimum of each unit $ht$ in each time period $t$ and representative day $dt$ (MW)
$R3^{ns}_{ht}$ tertiary offline reserve capability of each unit $ht$ (MW)
$RR^{dn,15}_{ht}$ ramp-down capability of each unit $ht$ during a 15-min time interval (MW/min)
$RR^{dn,30}_{ht}$ ramp-down capability of each unit $ht$ during a 30-min time interval (MW/min)
$RR^{dn,60}_{ht}$ ramp-down capability of each unit $ht$ during a 60-min time interval (MW/min)
$RR^{up,15}_{ht}$ ramp-up capability of each unit $ht$ during a 15-min time interval (MW/min)
$RR^{up,30}_{ht}$ ramp-up capability of each unit $ht$ during a 30-min time interval (MW/min)
$RR^{up,60}_{ht}$ ramp-up capability of each unit $ht$ during a 60-min time interval (MW/min)
$Tolerancelevel_{th,dt}$ desired tolerance level of each thermal unit $th$ in each representative day $dt$, for the minimum income condition order activation/deactivation check (p.u.)
$UT_{ht}$ minimum up-time of each unit $ht$ (h)
$Z^{2-}_{th,t,dt}$ desired cost coefficient added in the secondary-down reserve provision cost function of each thermal unit $th$ in each time period $t$ and representative day $dt$, when submitting a minimum income condition order (€/MW)
$Z^{2+}_{th,t,dt}$ desired cost coefficient added in the secondary-up reserve provision cost function of each thermal unit $th$ in each time period $t$ and representative day $dt$, when submitting a minimum income condition order (€/MW)
$Z^{3nsp}_{th,t,dt}$ desired cost coefficient added in the non-spinning (offline) tertiary-up reserve provision cost function of each thermal unit $th$ in each time period $t$ and representative day $dt$, when submitting a minimum income condition order (€/MW)
$Z^{3sp-}_{th,t,dt}$ desired cost coefficient added in the spinning tertiary-down reserve provision cost function of each thermal unit $th$ in each time period $t$ and representative day $dt$, when submitting a minimum income condition order (€/MW)
$Z^{3sp+}_{th,t,dt}$ desired cost coefficient added in the spinning tertiary-up reserve provision cost function of each thermal unit $th$ in each time period $t$ and representative day $dt$, when submitting a minimum income condition order (€/MW)
$Z^{e}_{th,t,dt}$ desired cost coefficient added in the minimum average

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