Resource-specific Orders in European Day-ahead Market Under Different Pricing Rules

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***Abstract*—This paper addresses two issues that concern the electricity market participants under the European day-ahead market (DAM) framework, namely the feasibility of the attained schedules and the non-confiscation of cleared volumes. To address the first issue, new resource-specific orders, i.e., thermal orders for thermal generating units, demand response orders for load responsive resources, and energy limited orders for storage resources, are proposed and incorporated in the existing European DAM clearing problem. To address the second issue, two approaches which lead to a non-confiscatory market are analyzed: ① discriminatory pricing with side-payments (U.S. paradigm); and ② non-discriminatory pricing excluding out-of-money orders (European paradigm). A comparison is performed between the two approaches to investigate the most appropriate pricing rule in terms of social welfare, derived revenues for the sellers, and efficiency of the attained results. The proposed model with new resource-specific products is evaluated in a European test system, achieving robust solutions. The feasibility of the attained schedules is demonstrated when using resource-specific orders compared with block orders. Finally, the results indicate the supremacy of discriminatory pricing with side-payments compared with the current European pricing rule.**

***Index Terms*—Day-ahead market, demand response, energy storage, non-confiscatory market, pricing, thermal order.**

Nomenclature

A. Sets and Indices

$b \in \mathcal{B}$	Step of supply order or demand order
$eg \in \mathcal{EG}_z$	Exclusive group of block orders in bidding zone z
$f \in \mathcal{F}$	Step of start-up process of thermal order
$l \in \mathcal{L}$	Index of interconnection
$L_{rmp} \subseteq \mathcal{L}$	Set of interconnections subject to ramping restrictions on power flow variations between succesive hours
$o \in \mathcal{O}_z$	Order submitted to bidding zone z, where $\mathcal{O} = \mathcal{DO} \cup \mathcal{SO} \cup \mathcal{BO} \cup \mathcal{THO} \cup \mathcal{DRO} \cup \mathcal{ELO}$, $\mathcal{DO}$ denotes demand orders; $\mathcal{SO}$ denotes supply orders; $\mathcal{BO}$ denotes block orders ($\mathcal{LBO} \subseteq \mathcal{BO}$, $\mathcal{LBO}$ denotes linked block orders); $\mathcal{THO}$ denotes thermal orders; $\mathcal{DRO}$ denotes demand response orders; and $\mathcal{ELO}$ denotes energy limited orders
$SO_{lg} \subseteq \mathcal{SO}$	Orders subject to load gradient condition
$SO_{mic} \subseteq \mathcal{SO}$	Orders subject to the minimum income condition
$t \in \mathcal{T}^{ext}$	Index of hourly period, where $\mathcal{T}^{ext} = \mathcal{T}^{past} \cup \mathcal{T}$, $\mathcal{T}$ includes the 24 hourly trading periods, $\mathcal{T}^{past}$ includes the hours preceding the first trading period
$z \in \mathcal{Z}$	Index of bidding zone

B. Parameters

$A_{z,so}$, $A_{z,bo}$	Elements of incidence matrices denoting if orders so and bo belong to bidding zone z
$A_{bo,lbo}, A_{bo,eg}$	Elements of incidence matrices denoting if block order bo is linked with linked block order lbo or belongs to exclusive group eg
$AR_{bo}^{\min}$	The minimum acceptance ratio of block order bo
$ATC_{l,t}^{\min}$, $ATC_{l,t}^{\max}$	The minimum and maximum available transfer capacities of interconnection l in period t (MW)
$BP_{dro}^{\min}$	The minimum baseload period of order dro (hour)
$DP_{dro}^{\min}, DP_{dro}^{\max}$	The minimum and maximum delivery periods of order dro (hour)
$E_{elo}^{ch}, E_{elo}^{dch}$	Daily energy quantities offered by order elo for charging and discharging (MWh)
$E_{elo}^{\max}$	The maximum storage capacity of order elo (MWh)
$FA_{dro}^{\max}$	The maximum frequency of activations of order dro in course of trading day
G_{so}^{up}, G_{so}^{dn}	Increasing and decreasing gradients of supply order so subject to a load gradient condition (MW/h)
$IF_{elo,t}$	Energy inflow of order elo in period t (MWh)
$L_{dro}^{pickup}, L_{dro}^{drop}$	Load pickup and drop rates of order dro (MW/h)

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$LZ_{z,l}$ Parameter denoting that interconnection l starts from bidding zone z (equal to 1) and ends to bidding zone z (equal to -1)

M Large constant

n_{elo} Cycle efficiency of order elo

P_o, Q_o Price-quantity pair of order o (€/MWh, MWh)

$Q_o^{\min}, Q_o^{\max}$ The minimum and maximum offered quantities of order o (MWh)

$Q_{tho,f}^{su}$ Energy level of step f of start-up process of thermal order tho (MWh)

$R_{tho}^{up}, R_{tho}^{dn}$ Ramp up and down rates of thermal order tho (MW/h)

$R_{z,t}^{up}, R_{z,t}^{dn}$ Ramp up and down limits of net position for bidding zone z in period t (MW/h)

$R_{l,t}^{up}, R_{l,t}^{dn}$ Ramp up and down limits of power flow in interconnection l and period t (MW/h)

SUC_{tho} Start-up cost of thermal order tho (€/start-up)

$T_{tho}^{syn}, T_{tho}^{su}, T_{tho}^{sd}$ Synchronization, start-up, and shut-down time of thermal order tho (hour)

$UT_{tho}^{\min}, DT_{tho}^{\min}$ The minimum up and down time of thermal order tho (hour)

$VT_{so}^{mic}, FT_{so}^{mic}$ Variable and fixed terms of supply order so subject to a minimum income condition (€/MWh, €)

V_o^{req} The minimum required daily revenue of order o, where $o \in \mathcal{SO} \cup \mathcal{THO} \cup \mathcal{DRO} \cup \mathcal{ELO}$ (€)

V_o^{atn} Attained market revenue of order o submitted with a minimum income condition, where $o \in \mathcal{SO} \cup \mathcal{THO} \cup \mathcal{DRO} \cup \mathcal{ELO}$ (€)

W_{bo} Welfare of block order bo (€)

C. Variables

$\lambda_{z,t}$ Dual variable of net position of bidding zone z in period t

$\mu_{z,t}^{up}, \mu_{z,t}^{dn}$ Dual variables of ramping limitation on net position of bidding zone z in period t

$e_{elo,t}$ Energy level of order elo in period t (MWh)

$ex_{l,t}$ Power exchange in interconnection l in period t (MWh)

$p_{z,t}$ Net position of bidding zone z in period t (MWh)

$q_{o,t}$ Cleared quantity of order o in period t (MWh)

$q_{tho,t}^{su}, q_{tho,t}^{sd}$ Cleared quantities of order tho in start-up and shut-down statuses in period t (MWh)

$q_{elo,t}^{ch}, q_{elo,t}^{dch}$ Cleared charging and discharging quantities of order elo in period t (MWh)

u_o Binary variable representing clearing status of order o

$u_{tho,t}^{syn}, u_{tho,t}^{su}, u_{tho,t}^{disp}, u_{tho,t}^{sd}$ Binary variables denoting that order tho is in synchronization, start-up, normal dispatch, and shut-down clearing statuses in period t

$u_{elo,t}^{ch}, u_{elo,t}^{dch}$ Binary variables denoting that order elo is in charging and discharging clearing statuses in period t

x_o Acceptance ratio of order o

$y_{o,t}, z_{o,t}$ Binary variables which are equal to 1 if clearance of an order begins and ends in period t

I. Introduction

As a main pillar towards the development of a single European electricity market [1], the coupling of national day-ahead markets (DAMs) based on implicit allocation of cross-border capacity was legally enforced through ENTSO-E network code on capacity allocation and congestion management and the respective regulation [2]. Several steps have been accomplished to achieve the practical implementation of this venture [3]. Currently, the "Multi-regional Coupling" covers more than 85% of the European power consumption. The DAMs in this region are cleared through the "Euphemia" algorithm [4]. Except from hybrid hourly orders (stepwise or piece-wise price-quantity pairs) and prezzo unico nazionale (PUN) orders (Italian peninsula), the Euphemia solver also supports other order types for managing techno-economic characteristics of the resources, such as block orders and complex orders [4]. These orders introduce non-convexities in the market clearing problem and thus, necessitate a special handling in the formulation.

Even though block and complex orders embed some of the techno-economic characteristics of thermal generating units, they are not able to capture detailed operating constraints. This issue has been raised by stakeholders in Europe, and the ideas of the incorporation of thermal orders (THOs) have emerged [5], which would better simulate the operating constraints of these resources but without proceeding to modeling details. The incorporation of THOs would be of particular interest in unit-based schemes (e. g., Italy, Greece), where each unit submits separate orders and constitutes an individual balance perimeter. In unit-based schemes, the participant has a strong motivation to create a market schedule, which is as close as possible to the real power trajectory of a unit. In contrast, in portfolio-based bidding schemes, the portfolio managers bid directly for larger portfolios which may include generating units, demand and storage assets, and/or power exchanges with neighboring bidding zones. Then, they allocate the overall bid to their resources according to their own criteria so that the overall (portfolio) market schedule is respected.

THOs could also contribute to a more efficient integration of renewable energy sources (RESs), due to their flexibility to adapt more accurately to changing net load (load minus RES) conditions compared with block orders.

At the same time, a gradual transformation is attempted from a conventional-resource market to the one with widespread diffusion of renewable generation [6]. Alongside, the integration of energy storage facilities including pumped-hydro storage, batteries and electric vehicle fleets [7], as well as the active demand-side participation [8], has become an important policy objective. The need for a “shift from the abstract bidding format approach to much more resource-specific products” [9] for such types of resources has also been identified. New “loop orders” in Epexspot [10] bundle buy and sell blocks in an attempt to represent the charging and discharging phases of a storage resource in a more accurate manner. This highlights the need for a continuous update of the bidding formats as the needs of market agents evolve [9].

In terms of clearing, the European DAM constitutes a non-convex problem since binary variables are used for the modeling of indivisible market orders. Pricing rules in such non-convex auctions have been put under scrutiny by the scientific community [11], [12], since it is difficult to find uniform prices that guarantee total cost recovery for the participants and to avoid the so-called “economic confiscation” phenomenon. In other words, the marginal clearing price (MCP) reflects the variable or incremental cost components of the offers but not the fixed cost components which introduce non-convexities (e. g., start-up or no-load cost). To render the market non-confiscatory, different pricing rules have emerged, especially in the U.S. and the E.U. power markets [13], which are summarized as follows.

1) Discriminatory pricing with side-payments (Case A): a uniform price is obtained from market clearing and the additional side-payments (uplifts) are provided for fixed costs that could not be recovered through uniform prices. This pricing rule is generally followed by the U. S. power markets, e.g., CAISO [14] or the Irish paradigm [15]. The out-of-the-market settlement of these make-whole payments brings forth some skepticism about their transparency, although the way of their calculation is strictly defined in the market rules. In the results, however, it is proven that the side-payments may represent a very small portion of the total revenues of the producers.

2) Non-discriminatory pricing internalizing fixed costs (Case B): the price formation considers the problem non-convexities in an attempt to reflect the participants’ fixed costs as well. References [16]-[18] seek to minimize the side-payments by allocating the fixed operational costs in the marginal prices perceived by the generating units. A real-case example is the “hybrid pricing” of NYISO [19] or the “extended locational marginal pricing” of MISO [20], which includes start-up and no-load costs in pricing.

3) Non-discriminatory pricing excluding out-of-money orders (Case C): a uniform price is derived from market clearing, which is the final settlement price. However, the appropriate controls are included in the algorithm to ensure that no market order is cleared which incurs a loss to the participant. The concept of removing paradoxically accepted orders (PAOs) from the final market solution has applications in most European DAMs [4]. In the results, it is proven that this market order exclusion leads to higher final revenues for the producers and thus higher costs for the end consumers, compared with the additional burden incurred by the side payments under Case A.

Finally, for example, compared with the U.S. system, one idea of the European model is the simplicity of the bidding formats, e.g., block orders. Our position is that this is a matter of participant choice and not a matter that should be predefined from a market-design point of view. Put it differently, both choices could be provided to the participants (e. g., block orders and resource-specific orders), so that they can decide which is the best option for them in everyday operation. With regards to the algorithm complexity, the mathematical problem formulation under the inclusion of resource-specific orders is tractable in the case study examined in this paper. Notably, the execution time is lower in Case A than that in Case C, which involves an iterative process.

Several research works have been proposed to appropriately model the block and complex orders under the European framework, in order to deal with non-convexities and to appropriately handle the PAOs. Table I summarizes the main features of the state of the art. As shown, most research works include block orders, whereas fewer add the linked block orders, the exclusive group of block orders, the Prezzo Unico Nazionale (PUN), and the minimum income condition (MIC) orders. To the best of the authors’ knowledge, there is no literature dealing with resource-specific orders under the European DAM clearing framework. In terms of pricing, most of research works utilize one pricing scheme. Notably, the research on the European market framework employs pricing rule of Case C.

In [16], a minimum uplift pricing approach is presented based on a decentralized formulation, where the problems of generators and market operators are simultaneously solved. In [17], a non-convex market settlement regime is proposed, where the prices also incorporate an uplift account. The market is cleared considering block orders, and the PAOs are compensated without any out-of-the-market process. The DAM is cleared with block orders in [18] using a bi-level programming model. The execution or rejection of the block orders is resolved at the upper level, whereas the lower level is used for the computation of market prices.

Reference [21] presents a mathematical approach for the solution of a multi-area dispatch, in which the production and demand of the same area may be cleared in different prices. The main principle is the formulation of a mixed complementarity problem for the system equilibrium conditions, in which the supply and demand are associated to explicitly or implicitly defined prices. The simulation results in [22] argue against restricting the use of blocks in the DAM, in terms of size, time span, and the number of blocks (per participant/per day).

A revenue-constrained market clearing method is studied in [23], where a primal-dual formulation aims at finding adequate prices that fulfill the minimum revenue requirements of all participants. Reference [24] assesses the impact of the pricing rule on the long-term investment incentives, by utilizing a long-term capacity expansion model. Results show that the linear pricing rule (non-discriminatory pricing) does not necessarily produce higher prices than the non-linear rule (discriminatory pricing). In fact, the linear pricing can lower the price since it attracts generation technologies with lower variable costs.

TABLE I
MAIN FEATURES OF STATE OF THE ART

Reference	Model	Block order	Linked block order	Exclusive group of block orders	PUN order	MIC order	THO, DRO, ELO	Number of zones	Case (pricing rule)
[16]	LP	No	No	No	No	No	No		B
[17]	MILP	Yes	No	No	No	No	No		B
[18]	MILP	Yes	No	No	No	No	No		B
[21]	MCP	No	No	No	Yes	No	No	5	C
[22]	MILP	Yes	No	No	No	No	No		C
[23]	MILP	No	No	No	No	No	No	24	B
[24]	MILP	No	No	No	No	No	No		A, B
[25]	MPEC	Yes	Yes	No	No	No	No	10	C
[26]	MILP	Yes	Yes	Yes	No	Yes	No	42	C
[27]	LP,MCP	Yes	No	No	No	No	No	42	C
[28]	MILP	Yes	Yes	Yes	No	Yes	No	42	C
[29]	MILP	Yes	No	No	No	No	No		C
[30]	LP	No	No	No	No	No	No	1	A
[31]	MILP	No	No	No	No	Yes	No	300	C
[32]	MILP, MCP	Yes	Yes	Yes	Yes	Yes	No	42	C
[33]	MILP	Yes	No	No	Yes	Yes	No	3	C
[34]	MILP	Yes	No	No	Yes	No	No	6	
[35]	MILP	Yes	No	No	Yes	No	No	6	C
[36]	MILP	Yes	No	No	Yes	No	No	22	C
[37]	MIQCP	Yes	Yes	No	Yes	Yes	No	53	C
[38]	MILP, MCP	Yes	No	No	Yes	Yes	No	14	C
[39]	MILP	Yes	Yes	No	No	Yes	No	1	C
[40]	MILP	Yes	Yes	Yes	No	Yes	No	1	C
[41]	MILP	Yes	No	No	No	Yes	No		
This paper	MILP	Yes	Yes	Yes	No	Yes	Yes	42	A, C

Note: DRO and ELO are short for demand response order and energy limited order, respectively; and in this table only, MCP refers to the mixed complementarity problem.

In [25], the pricing, modeling, and clearing of the European DAM are presented, incorporating simple, block, and flexible hourly orders, and transmission network constraints. The optimization problem is formulated as a relaxed mathematical programming with equilibrium constraints (MPECs) and is decomposed into a mixed-integer quadratic program (MIQP) and a linear pricing problem. In [26], an iterative algorithm is presented for the European DAM clearing, incorporating block orders, flexible hourly orders, complex orders, and transmission and net position constraints. During the iterative process, the PAOs are effectively removed from the order book. Further, [27] presents the DAM clearing with two different methods, i.e., a linear programming (LP) model and a mixed complementarity problem. The mixed complementarity problem can simulate adjustable product types by incorporating non-linear mixed pricing rules, but it is computationally demanding. In contrast, the LP model is computationally efficient but not flexible enough to handle an extended variety of adjustable supply/demand block orders.

A mathematical formulation that incorporates various market products and transmission constraints of the European DAM is proposed in [28]. The problem is formulated as a mixed-integer linear programming (MILP) model and is solved within an iterative algorithm for the handling of paradoxically accepted block and the minimum income orders. In [29], a primal-dual approach is presented for the DAM clearing with MIC and block orders. An MILP formulation of the market clearing problem is presented, avoiding the introduction of auxiliary variables and relying on an exact linearization of the MIC. Additional MILP formulations are discussed, namely the maximization of the traded volume and the minimization of opportunity costs of paradoxically rejected block bids. An ex-post multipart pricing scheme, referred to as the dual pricing algorithm, is proposed in [30] for a revenue neutral and non-confiscatory DAM. Bilevel programming is used in [31] for solving the DAM, where generation revenue constraints are explicitly incorporated in the problem formulation. The bilevel mixed-integer non-linear program is transformed into an equivalent single-level MILP using a primal-dual transformation.

In [32], the DAM clearing incorporates the PUN price of the Italian market, along with other European market orders, considering an available transfer capacity (ATC) based network representation and flow-ramping constraints. A master problem formulated as MILP is solved iteratively incorporating all European market orders except for the PUN orders; this problem removes the PAOs from the order book. Then, 24 hourly PUN sub-problems formulated as mixed complementarity problems are solved sequentially. Reference [33] provides an alternative MILP formulation for uniform purchase prices (such as the PUN price), while [34] analyzes the effects of introducing block orders into the Italian market in terms of computation time, PUN level, and the number of paradoxically rejected orders. Reference [35] formulates the DAM clearing with a uniform purchase price and zonal selling prices, as a computationally tractable MILP problem solved for the Italian market, and the model is extended in [36] to include curtailable block orders and more bidding zones. References [37] and [38] further analyze the clearing of the block and the PUN orders.

Reference [39] extends the European energy-only DAM by incorporating the reserve market and satisfying the relevant constraints at 15-min, 30-min, and hourly levels. The MIC is also extended to consider the revenues from the reserve market in addition to the energy revenues. Reference [40] concludes that the overuse of block and MIC orders may reduce the flexibility in the offered energy and therefore, may lead to high deviations in hourly MCPs and non-feasible market schedules.

Finally, the combination of the minimum income, load gradient, and auxiliary scheduled stop complex conditions is examined in [41].

The contributions of this paper are as follows.

1) Inclusion of "resource-specific" orders in the European DAM clearing problem, by extending a previous market clearing formulation [28] that incorporates the main functionalities of the Euphemia algorithm (benchmark model). Three new types of orders are proposed and modeled, namely the THOs, DROs, and the energy ELOs. The scope is to include market products that better fit to the dispatch profiles of these resources.

2) Analysis and comparison of different pricing rules that ensure economic non-confiscation of all order types. For Case A, discriminatory pricing with ex-post side-payments is considered, while for Case C, a modeling framework is constructed where all orders are subject to revenue-constrained controls during an iterative process. Case B is not investigated in this work.

3) The proposed modeling framework is evaluated using the ENTSO-E zonal system, aiming to assess the computational complexity of the benchmark model in the presence of the new order types.

The remainder of this paper is organized as follows. Section II provides the problem formulation and the solution algorithm. Section III elaborates on the case study and results. The basic conclusions of the conducted research are drawn in Section IV along with ideas for future consideration.

II. Problem Description

A. Mathematical Formulation

The proposed DAM clearing model is mathematically formulated as an MILP problem. Equation (1) maximizes the social welfare, i. e., the total load utility of demand orders (*do*) minus the offer cost of supply orders (*so*), block orders (*bo*), thermal orders (*tho*), demand response orders (*dro*), and energy limited orders (*elo*).

$$\begin{aligned}\max F = & \sum_{do \in \mathcal{DO}} \sum_{b \in \mathcal{B}} \sum_{t \in \mathcal{T}} P_{do,b,t} Q_{do,b,t} x_{do,b,t} - \\ & \sum_{so \in \mathcal{SO}} \sum_{b \in \mathcal{B}} \sum_{t \in \mathcal{T}} P_{so,b,t} Q_{so,b,t} x_{so,b,t} - \\ & \sum_{bo \in \mathcal{BO}} \sum_{t \in \mathcal{T}} P_{bo} Q_{bo,t} x_{bo} - \\ & \sum_{tho \in \mathcal{THO}} \sum_{t \in \mathcal{T}} (P_{tho,t} q_{tho,t} + SUC_{tho} y_{tho,t}) - \\ & \sum_{dro \in \mathcal{DRO}} \sum_{t \in \mathcal{T}} P_{dro,t} q_{dro,t} - \\ & \sum_{elo \in \mathcal{ELO}} \sum_{t \in \mathcal{T}} (P^{dch}_{elo,t} q^{dch}_{elo,t} - P^{ch}_{elo,t} q^{ch}_{elo,t}) \end{aligned} \quad (1)$$

1) System Constraints

Equation (2) is the power balance equation for each trading period and bidding zone z. In (3), the net position of zone is equal to the algebraic sum of all exchanges with neighboring zones. The values in brackets at the right-hand side of (3) are the dual variables (Lagrange multipliers) used for the computation of the MCPs (see Section II-B). An ATC-based model is adopted herein, and a flow-based network representation could also be used.

$$\begin{aligned} & \sum_{so \in \mathcal{SO}_z} \sum_{b \in \mathcal{B}} Q_{so,b,t} x_{so,b,t} + \sum_{bo \in \mathcal{BO}_z} Q_{bo,t} x_{bo} + \\ & \sum_{tho \in \mathcal{THO}_z} q_{tho,t} + \sum_{dro \in \mathcal{DRO}_z} q_{dro,t} + \\ & \sum_{elo \in \mathcal{ELO}_z} (q^{dch}_{elo,t} - q^{ch}_{elo,t}) - \sum_{do \in \mathcal{DO}_z} \sum_{b \in \mathcal{B}} Q_{do,b,t} x_{do,b,t} = \\ & \sum_{l \in \mathcal{L}} LZ_{z,l} \cdot ex_{l,t} \quad \forall z \in \mathcal{Z}, t \in \mathcal{T} \end{aligned} \quad (2)$$

$$p_{z,t} = \sum_{l \in \mathcal{L}} LZ_{z,l} \cdot ex_{l,t} \quad \forall z \in Z, t \in T \quad [\lambda_{z,t}] \quad (3)$$

Inequality (4) expresses the minimum and maximum exchange limits in the interconnections based on the available transfer capacities. Notably, high-voltage direct current (HVDC) lines with high ramping capabilities may lead to big variations of the power flows between two consecutive trading periods. In this case, the inadequate ramp capabilities and available reserves of generators may not be able to cover possible rapid changes in real time. To this end, (5) imposes ramping limitations on the variations of each zone's net position between successive hours [32], while (6) enforces ramping restrictions on the power flow variations in the interconnections [42].

$$ATC^{\min}_{l,t} \le ex_{l,t} \le ATC^{\max}_{l,t} \quad \forall l \in \mathcal{L}, t \in \mathcal{T} \quad (4)$$

$$-R^{dn}_{z,t} \le p_{z,t} - p_{z,t-1} \le R^{up}_{z,t} \quad \forall z \in \mathcal{Z}, t \in \mathcal{T} \quad [\mu^{up}_{z,t}, \mu^{dn}_{z,t}] \quad (5)$$

$$-R^{dn}_{l,t} \le ex_{l,t} - ex_{l,t-1} \le R^{up}_{l,t} \quad \forall l \in \mathcal{L}_{rmp}, t \in \mathcal{T} \quad (6)$$

2) Existing Market Orders

Constraints (7)-(11) model the clearing conditions of orders that are currently tradable in the European DAMs. More specifically, (7) denotes the upper clearing limit of simple hourly demand and supply orders. In (8), ramping limitations are enforced in the cleared quantities of successive trading periods for supply orders subject to the load gradient condition (Iberian market). These constraints are not imposed for the first trading period t_1. In (9), the cleared quantity of a block order is delimited between its minimum and maximum acceptance ratios (the latter is equal to 1). Constraint (10) determines the relationship between a linked block order *lbo* and its "parent" block order *bo*. The main purpose of linked block orders is to assist producers in scheduling their generating units either at zero production or above their technical minimum production.

$$0 \le x_{o,b,t} \le 1 \quad \forall o \in \mathcal{DO} \cup \mathcal{SO}, b \in \mathcal{B}, t \in \mathcal{T} \tag{7}$$

$$-G_{so}^{dn} \le \sum_{b \in \mathcal{B}} Q_{so,b,t} x_{so,b,t} - \sum_{b \in \mathcal{B}} Q_{so,b,t-1} x_{so,b,t-1} \le G_{so}^{up} \quad \forall so \in \mathcal{SO}_{lg}, t \in \{T | t > t_1\} \tag{8}$$

$$AR_{bo}^{\min} u_{bo} \le x_{bo} \le u_{bo} \quad \forall bo \in \mathcal{BO} \tag{9}$$

$$0 \le x_{lbo} \le \sum_{bo \in \mathcal{BO}} A_{bo,lbo} x_{bo} \quad \forall lbo \in \mathcal{LBO} \tag{10}$$

$$\sum_{bo \in \mathcal{BO}} A_{bo,eg} u_{bo} \le 1 \quad \forall eg \in \mathcal{EG} \tag{11}$$

Inequality (11) models the clearing condition of block orders belonging to an exclusive group *eg*. Between the various block orders submitted by a participant within an exclusive group, the optimization criterion selects the one that maximizes the objective function. Such order type allows participants to propose for different production patterns. The disadvantage is that the algorithm may only choose between the pre-defined blocks by the participant, without being flexible to optimally schedule the output of the generating units at an hourly level depending on system conditions.

3) THOs

The proposed THOs model the successive operating states of a thermal generating unit upon start-up. As shown in Fig. 1, the clearing of a THO begins at period t_1 ($y_{tho,t}$=1) and remains in effect ($u_{tho,t}$=1) until period t_5 ($z_{tho,t}$=1). Once accepted, the THO follows four consecutive operating phases: ① synchronization, during which the plant injection into the system is zero; ② start-up, which is a step-wise soak trajectory from the synchronization load to the minimum quantity of the THO; ③ normal dispatch, during which the cleared quantity varies between the minimum and the maximum order quantities, and ④ shut-down, which is a stepwise desynchronization process with a linear decrease rate from the minimum quantity to zero production.

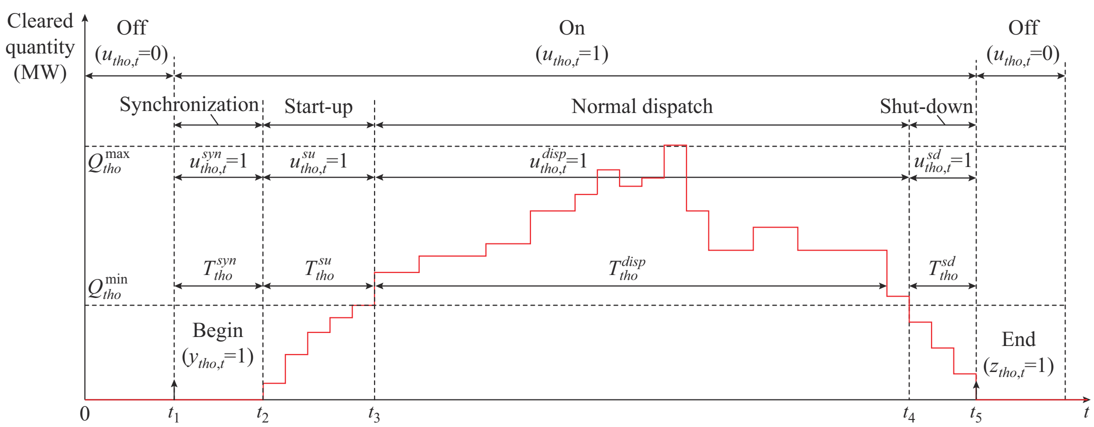

Fig. 1. Operating states of a THO.

Constraints (12)-(16) model the aforementioned operating states. Equations (12) and (13) ensure that the THO enters the synchronization status immediately after clearing and the start-up status upon that. In (14), the cleared quantity during the start-up status follows a user-defined sequence of megawatt values. In (15), the THO enters the shut-down status, during which the cleared quantity decreases linearly from the minimum order quantity to zero in (16).

$$u_{tho,t}^{syn} = \sum_{\tau = t - T_{tho}^{syn} + 1}^{t} y_{tho,\tau} \quad \forall tho \in \mathcal{THO}, t \in \mathcal{T} \tag{12}$$

$$u_{tho,t}^{su} = \sum_{\tau = t - T_{tho}^{syn} - T_{tho}^{su} + 1}^{t - T_{tho}^{syn}} y_{tho,\tau} \quad \forall tho \in \mathcal{THO}, t \in \mathcal{T} \tag{13}$$

$$q_{tho,t}^{su} = \sum_{f=1}^{T_{tho}^{su}} y_{tho,t-T_{tho}^{syn}-f+1} Q_{tho,f}^{su} \quad \forall tho \in \mathcal{THO}, t \in \mathcal{T} \tag{14}$$

$$u_{tho,t}^{sd} = \sum_{\tau = t+1}^{t + T_{tho}^{sd} - 1} z_{tho,\tau} \quad \forall tho \in \mathcal{THO}, t \in \mathcal{T} \tag{15}$$

$$q_{tho,t}^{sd} = \sum_{\tau = t}^{t + T_{tho}^{sd} - 1} z_{tho,\tau} (\tau - t) \frac{Q_{tho}^{\min}}{T_{tho}^{sd}} \quad \forall tho \in \mathcal{THO}, t \in \mathcal{T} \tag{16}$$

Constraints (17) and (18) represent the minimum up/down time limitation of the THO. The logical relations of the clearing status binary variables are provided in (19)-(23). For example, (19) ensures that a THO is in only one clearing status in a given trading hour. Note that constraints (22) and (23) can be omitted without altering the problem solution; they are proposed for a faster execution. Constraints (24) and (25) describe the upper and lower limits for the cleared quantity of a THO, respectively. Finally, (26) imposes hourly ramping restrictions on the cleared quantities between consecutive trading periods.

$$\sum_{\tau = t - UT_{tho}^{\min} + 1}^{t} y_{tho,\tau} \le u_{tho,t} \quad \forall tho \in \mathcal{THO}, t \in \mathcal{T} \tag{17}$$

$$\sum_{\tau = t - DT_{tho}^{\min} + 1}^{t} z_{tho,\tau} \le 1 - u_{tho,t} \quad \forall tho \in \mathcal{THO}, t \in \mathcal{T} \tag{18}$$

$$u_{tho,t} = u_{tho,t}^{syn} + u_{tho,t}^{su} + u_{tho,t}^{disp} + u_{tho,t}^{sd} \quad \forall tho \in \mathcal{THO}, t \in \mathcal{T} \tag{19}$$

$$y_{tho,t} - z_{tho,t} = u_{tho,t} - u_{tho,t-1} \quad \forall tho \in \mathcal{THO}, t \in \mathcal{T} \tag{20}$$

$$y_{tho,t} + z_{tho,t} \leq 1 \quad \forall tho \in \mathcal{THO}, t \in \mathcal{T} \tag{21}$$

$$y_{tho,t} \leq u_{tho,t} \quad \forall tho \in \mathcal{THO}, t \in \mathcal{T} \tag{22}$$

$$z_{tho,t+1} \leq u_{tho,t} \quad \forall tho \in \mathcal{THO}, t \in \mathcal{T} \tag{23}$$

$$q_{tho,t} \geq 0 \cdot u^{syn}_{tho,t} + q^{su}_{tho,t} + q^{sd}_{tho,t} + Q^{\min}_{tho} u^{disp}_{tho,t} \quad \forall tho \in \mathcal{THO}, t \in \mathcal{T} \tag{24}$$

$$q_{tho,t} \leq 0 \cdot u^{syn}_{tho,t} + q^{su}_{tho,t} + q^{sd}_{tho,t} + Q^{\max}_{tho} u^{disp}_{tho,t} \quad \forall tho \in \mathcal{THO}, t \in \mathcal{T} \tag{25}$$

$$-R^{dn}_{tho} u^{disp}_{tho,t} - M(z_{tho,t} + u^{sd}_{tho,t}) \leq q_{tho,t} - q_{tho,t-1} \leq R^{up}_{tho} u^{disp}_{tho,t} + M(u^{syn}_{tho,t} + u^{su}_{tho,t}) \quad \forall tho \in \mathcal{THO}, t \in \{\mathcal{T} | t > t_{ini}\} \tag{26}$$

4) DROs

A dispatchable consumer may not be able to provide its responsiveness unless during a minimum period of time, as provisioned in (27). Similarly, the dispatchable load may not be available during extended periods of time, thus a maximum delivery period is foreseen in (28). Limitations may also exist in the period between two successive activations; therefore, a minimum baseload period is ensured in (29). The participant may limit the frequency of activations in the course of a day, as per (30). Constraints (31)-(33) model the logical relationships of binary variables denoting the clearing status for the DROs. Again, (33) can be omitted without altering the problem solution.

$$\sum_{\tau=t-DP^{\min}_{dro}+1}^{t} y_{dro,\tau} \leq u_{dro,t} \quad \forall dro \in \mathcal{DRO}, t \in \mathcal{T} \tag{27}$$

$$\sum_{\tau=t+1}^{\tau=t+DP^{\max}_{dro}} z_{dro,\tau} \geq u_{dro,t} \quad \forall dro \in \mathcal{DRO}, t \in \mathcal{T} \tag{28}$$

$$\sum_{\tau=t-BP^{\min}_{dro}+1}^{t} z_{dro,\tau} \leq 1 - u_{dro,t} \quad \forall dro \in \mathcal{DRO}, t \in \mathcal{T} \tag{29}$$

$$\sum_{t \in T} y_{dro,t} \leq FA^{\max}_{dro} \quad \forall dro \in \mathcal{DRO} \tag{30}$$

$$y_{dro,t} - z_{dro,t} = u_{dro,t} - u_{dro,t-1} \quad \forall dro \in \mathcal{DRO}, t \in \mathcal{T} \tag{31}$$

$$y_{dro,t} + z_{dro,t} \leq 1 \quad \forall dro \in \mathcal{DRO}, t \in \mathcal{T} \tag{32}$$

$$z_{dro,t+1} \leq u_{dro,t} \quad \forall dro \in \mathcal{DRO}, t \in \mathcal{T} \tag{33}$$

Demand response resources usually respond to instructed variations of their load with high ramp capability. Occasionally, however, the full provision of resources may take some time; load pickup rates and load drop rates in (34) resemble the respective ramp rates of the generating units. Finally, the maximum and minimum offered quantities of a DRO are imposed in (35). Note that the synchronization, start-up, and shut-down phases presented earlier for THOs mimic specific power trajectory limitations of thermal turbines. In case such operating phases are considered appropriate also for the DROs, a similar modeling approach could be followed.

$$-L^{drop}_{dro} \leq q_{dro,t} - q_{dro,t-1} \leq L^{pickup}_{dro} \quad \forall dro \in \mathcal{DRO}, t \in \mathcal{T} \tag{34}$$

$$Q^{\min}_{dro} u_{dro,t} \leq q_{dro,t} \leq Q^{\max}_{dro} u_{dro,t} \quad \forall dro \in \mathcal{DRO}, t \in \mathcal{T} \tag{35}$$

5) ELOs

Energy storage resources are able to exploit the market price spreads between the periods of high and low demands. This strategy, referred to as arbitrage, is reflected in the last term of objective function (1) and involves purchasing low-price energy at off-peak hours (i.e., charging the storage resource) and selling it back to the DAM at a reasonably higher price (i.e., discharging the storage resource). The ELOs proposed here are intended to address generic storage constraints, facilitating the participation of various storage resources in the DAM (e.g., water reservoir or electrochemical batteries).

Constraints (36) and (37) impose the minimum and maximum discharging and charging capabilities of an ELO, respectively. Constraint (38) ensures that an ELO will not be cleared in charging and discharging statuses simultaneously, which is rational from a market design point of view. Note that this constraint can be omitted, since under normal trading behavior, the optimization criterion will ensure this condition. Equation (39) expresses the time-coupling energy balance, namely the state of charge decreases when discharging and increases when charging or inflows incur (e.g., in the case of pumped-hydro stations), accounting also for the efficiency of the charging-discharging cycle. The state of charge at the beginning of the trading horizon (i.e., t_{ini}) is determined in (40). For any other hours, the state of charge is bounded between the maximum and minimum storage limitations in (41). Finally, constraints (42) and (43) provide the opportunity to limit the total energy discharging and charging operation during the trading day, respectively.

$$Q^{dch,\min}_{elo} u^{dch}_{elo,t} \leq q^{dch}_{elo,t} \leq Q^{dch,\max}_{elo} u^{dch}_{elo,t} \quad \forall elo \in \mathcal{ELO}, t \in \mathcal{T} \tag{36}$$

$$Q^{ch,\min}_{elo} u^{ch}_{elo,t} \leq q^{ch}_{elo,t} \leq Q^{ch,\max}_{elo} u^{ch}_{elo,t} \quad \forall elo \in \mathcal{ELO}, t \in \mathcal{T} \tag{37}$$

$$u^{ch}_{elo,t} + u^{dch}_{elo,t} \leq 1 \quad \forall elo \in \mathcal{ELO}, t \in \mathcal{T} \tag{38}$$

$$e_{elo,t} = e_{elo,t-1} + IF_{elo,t} + n_{elo} q^{ch}_{elo,t} - q^{dch}_{elo,t} \quad \forall elo \in \mathcal{ELO}, t \in \mathcal{T} \tag{39}$$

$$e_{elo,t} = E^{ini}_{elo} \quad \forall elo \in \mathcal{ELO}, t = t_{ini} \tag{40}$$

$$0 \leq e_{elo,t} \leq E^{\max}_{elo} \quad \forall elo \in \mathcal{ELO}, t \in \mathcal{T} \tag{41}$$

$$\sum_{t \in \mathcal{T}} q^{dch}_{elo,t} \leq E^{dch}_{elo} \quad \forall elo \in \mathcal{ELO} \tag{42}$$

$$\sum_{t \in \mathcal{T}} q^{ch}_{elo,t} \leq E^{ch}_{elo} \quad \forall elo \in \mathcal{ELO} \tag{43}$$

6) Binary and Non-negative Variables

Constraint (44) defines the feasible space of the binary variables, while constraint (45) imposes the non-negative condition in the relevant continuous variables of the problem.

$$u_{bo}, u_{tho,t}, u_{dro,t}, u^{syn}_{tho,t}, u^{su}_{tho,t}, u^{disp}_{tho,t}, u^{sd}_{tho,t}, u^{ch}_{elo,t}, u^{dch}_{elo,t}, y_{tho,t}, z_{tho,t}, y_{dro,t}, z_{dro,t} \in \{0,1\} \quad \forall bo \in \mathcal{BO}, tho \in \mathcal{THO}, dro \in \mathcal{DRO}, elo \in \mathcal{ELO}, t \in \mathcal{T} \tag{44}$$

$$q_{tho,t}, q_{dro,t}, q^{su}_{tho,t}, q^{sd}_{tho,t}, q^{ch}_{elo,t}, q^{dch}_{elo,t}, e_{elo,t}, ex_{l,t} \geq 0 \quad \forall tho \in \mathcal{THO}, dro \in \mathcal{DRO}, elo \in \mathcal{ELO}, l \in \mathcal{L}, t \in \mathcal{T} \tag{45}$$

B. Price Formation

The DAM clearing model described above incorporates integer (binary) variables to model the various types of orders. As a result, an MILP problem is formulated and the attained dual variables do not determine the MCPs in a straightforward manner. The method used in this paper for the computation of MCPs is based on [43], according to which the binary variables are fixed to their optimal values and the same (now continuous) problem is re-solved to derive the shadow prices of all constraints. Most MILP solvers make this calculation inherently. Then, the hourly MCPs are computed using the following equation:

$$\pi_{z,t}=\lambda_{z,t}-(\mu^{up}_{z,t}-\mu^{up}_{z,t+1})+(\mu^{dn}_{z,t}-\mu^{dn}_{z,t+1}) \quad \forall z\in\mathcal{Z}, t\in\mathcal{T} \tag{46}$$

C. Solution Algorithm

As shown in Fig. 2, with regard to Case C, the iterative algorithm for the incorporation of resource-specific orders in the DAM clearing problem is as follows.

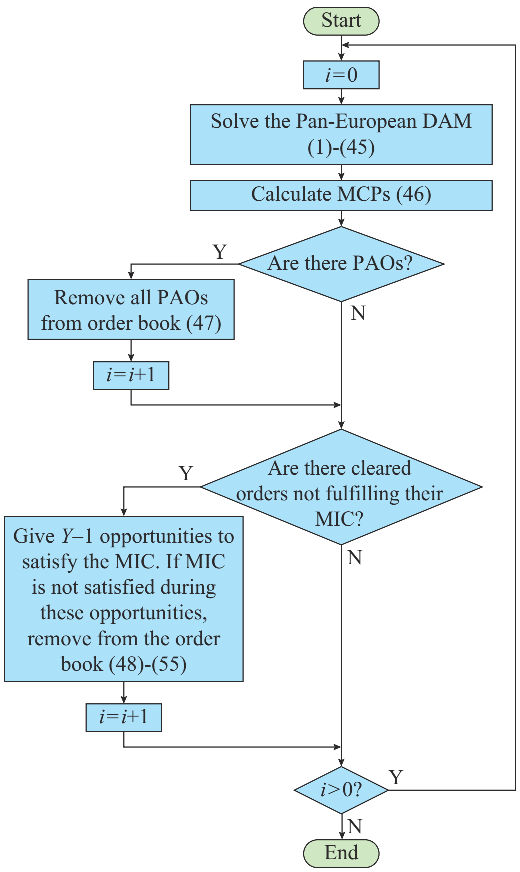

Fig. 2. Iterative algorithm.

1) *Step 1*: the DAM problem in (1)-(45) is solved first to attain the cleared volumes of all submitted orders. The optimization horizon is 24 hours.

2) *Step 2*: the MCPs of each bidding zone are calculated using (46).

3) *Step 3*: consecutive controls identify any: ① PAOs; ② supply orders, THOs, DROs, and ELOs that do not fulfill their MIC. PAOs are immediately excluded from the order book. For supply orders, THOs, DROs, and ELOs that do not fulfill their MIC in current iteration, the specific controls are applied as described below.

4) *Step 4*: in case where there are no PAOs and orders that do not meet their MIC, the algorithm terminates. Otherwise, the process continues with *Step 1*.

The respective algorithm for Case A includes only *Steps 1* and *2*. No order control is applied and the process terminates with a single iteration. Side-payments are then calculated ex-post.

1) Control of PAOs

In *Step 3* of each iteration, the welfare of each block order is calculated as:

$$W_{bo}=\sum_{t\in\mathcal{T}}\left[\sum_{z\in\mathcal{Z}}(A_{z,bo}\pi_{z,t})-P_{bo}\right]Q_{bo,t}\bar{x}_{bo}\quad \forall bo\in\mathcal{BO} \tag{47}$$

where $\bar{x}_{bo}$ is the optimal value of x_{bo} derived from *Step 1* of current iteration. In case the welfare is negative, the order is designated as PAO and is removed from the order book.

2) Control of Orders Under an MIC

The attained market revenue V^{atn}_{so} of each supply order submitted with an MIC condition is calculated as:

$$V^{atn}_{so}=\sum_{t\in\mathcal{T}}\sum_{b\in\mathcal{B}}\sum_{z\in\mathcal{Z}}(A_{z,so}\pi_{z,t})\bar{x}_{so,b,t}Q_{so,b,t}\quad\forall so\in\mathcal{SO}_{mic} \tag{48}$$

V^{atn}_{so} is compared with the revenue required by the participant V^{req}_{so}. The latter incorporates both the variable term VT^{mic}_{so} and the fixed term FT^{mic}_{so} of an MIC order:

$$V^{req}_{so}=VT^{mic}_{so}\sum_{t\in\mathcal{T}}\sum_{b\in\mathcal{B}}(\bar{x}_{so,b,t}Q_{so,b,t})+FT^{mic}_{so}\quad\forall so\in\mathcal{SO}_{mic} \tag{49}$$

If $V^{atn}_{so}\le V^{req}_{so}$, the order is removed from the order book. However, if the supply order is close to fulfil its MIC in a given iteration, Y opportunities are provided to the order for being accepted in the following iterations. Specifically, the "revenue ratio" is calculated in current iteration as:

$$V^{ratio}_{so}=\frac{V^{req}_{so}-V^{atn}_{so}}{V^{req}_{so}}\quad\forall so\in\mathcal{SO}_{mic} \tag{50}$$

If this ratio is lower than a specific threshold X (e.g., 10%), another $Y-1$ opportunities are provided to this order for meeting its MIC. Similar MIC controls are implemented for the newly proposed orders, based on the comparison between attained market revenues (51)-(52) and required revenues (53)-(55).

$$V^{atn}_{o}=\sum_{t\in T}\pi_{z,t}\bar{q}_{o,t}\quad\forall o\in\mathcal{THO}_z\cup\mathcal{DRO}_z \tag{51}$$

$$V^{atn}_{elo}=\sum_{t\in T}\pi_{z,t}(\bar{q}^{dch}_{elo,t}-\bar{q}^{ch}_{elo,t})\quad\forall elo\in\mathcal{ELO}_z \tag{52}$$

$$V^{req}_{tho}=VT_{tho}\cdot\sum_{t\in T}\bar{q}_{tho,t}+SUC_{tho}\quad\forall tho\in\mathcal{THO} \tag{53}$$

$$V^{req}_{dro}=VT_{dro}\cdot\sum_{t\in T}\bar{q}_{dro,t}\quad\forall dro\in\mathcal{DRO} \tag{54}$$

$$V^{req}_{elo}:\ \text{user-defined} \tag{55}$$

The derivation of market dearing process is given in Appendix A.

III. Case Study and Results

A. Case Study

The proposed model is applied in a test system comprising 42 European bidding zones (indicated by the abbreviations) and 72 interconnectors, as shown in Fig. 3. The net transfer capacities (NTCs) in continental Europe, the Nordpool region, and the six Italian bidding zones have been gathered from the ENTSO-E Transparency Platform [44] and TSO websites for year 2018. The respective ATC values have been calculated after subtracting the already nominated capacities from the NTC, and the already nominated capacities are generated in a random way for the purposes of this case study. The ATCs along with the techno-economic data of all orders used in this case study have been published in [45]. The THOs are submitted in the Greek (GR) bidding zone for the purposes of this case study. The demand bids comprise ten price-quantity steps per bidding zone and per hourly trading period. In terms of quantity, the first step represents the inelastic demand while the remaining steps represent the elastic demand. The assumption is that the elastic demand (sum of nine steps) is 30% of the total demand (sum of ten steps). In terms of price, the first step (inelastic demand) is priced at 1000 €/MWh. The remaining steps (elastic demand) follow a descending price trend and are closer to the actual MCPs for a typical day of year 2018 as taken by the ENTSO-E Transparency Platform [44].

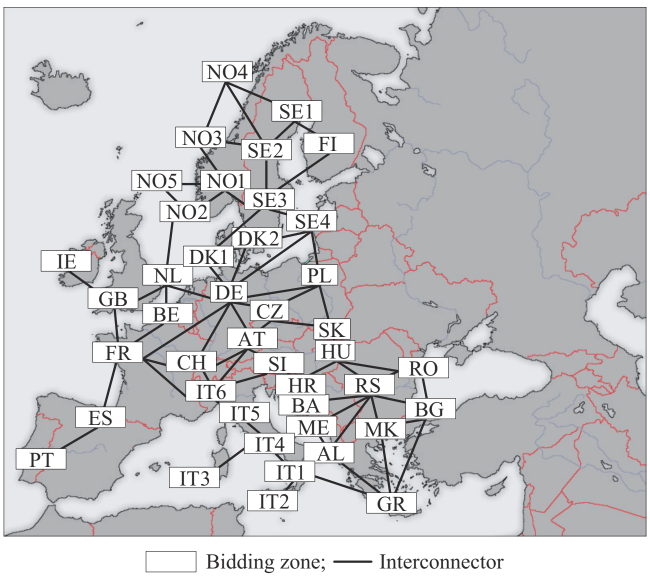

Fig. 3. European bidding zones and interconnectors.

For back-testing purposes, we first evaluate the performance of the benchmark model (i. e., without the proposed resource-specific orders) in a real-world market case. Specifically, the Greek DAM has been simulated for the 31 days of December 2021, by utilizing the real hybrid curves and block orders as published by the Hellenic Energy Exchange [46]. The actual and simulated DAM clearing prices are shown in Fig. 4, which demonstrates the convergence achieved. The average DAM clearing price for December 2021 is equal to 235.384 €/MWh, whereas the simulated one is equal to 235.498 €/MWh. The average price deviation is equal to 0.114 €/MWh, whereas the standard deviation of the differences is equal to 0.5398 €/MWh.

For comparison purposes, three test cases are examined below.

1) Case A. One-shot process includes only *Steps 1* and *2* of the algorithm, without any order control. To render the market non-confiscatory, additional make-whole payments are assumed.

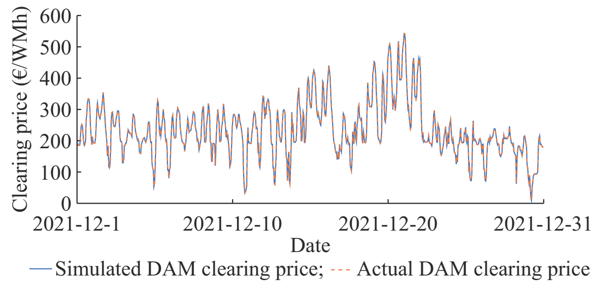

Fig. 4. Curves of actual and simulated DAM clearing prices.

2) Case C. The block orders, THOs, DROs, and ELOs which incur a negative welfare to their participants are removed from the order book, according to the description of Section II-C, to ensure non-confiscation.

3) Case BO. Similar with Case C with the exception that the THOs are substituted by comparable block and linked block orders. When a THO has a minimum up time longer than 24 hours, a respective 24-hour block order is created in Case BO with a quantity equal to the minimum quantity of the THO and a price equal to the average price of the THO over the 24 hours. On top of this block order, 24 hourly linked block orders are created at the same hourly price as the THO. When a THO has a minimum up time shorter than 24 hours, a respective exclusive group of orders is created in the Case BO. Each block of the exclusive group starts at each successive hour of the day and has a duration equal to the minimum up time of the respective THO.

B. Clearing of THOs

Typical examples of THO clearing are presented in Fig. 5 for the Greek bidding zone. The description below demonstrates that a feasible scheduling is attained using the proposed THOs.

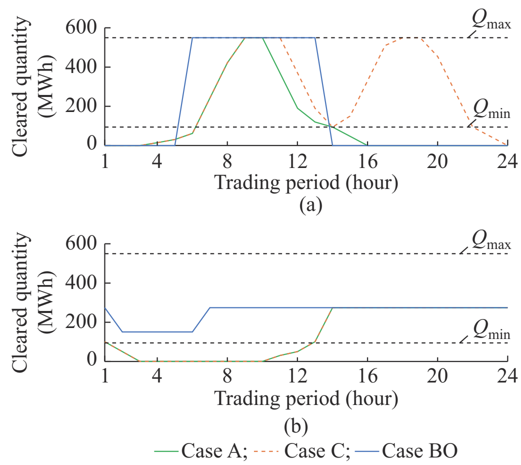

Fig. 5. Typical examples of THO clearing. (a) THO1. (b) THO2.

In Fig. 5(a), in Case A, the THO (THO1) follows a typical start-up/normal dispatch/desynchronization process, respecting a minimum up time of 8 hours. The same happens in Case C, however, the THO is cleared during more trading periods. This happens because several lower-cost THOs do not fulfill their MIC and are removed from the order book during the iterative process of Case C. Thereby, the prices increase and the THO in question covers its required revenue. A different production profile is cleared in Case BO based on the equivalent exclusive block order. This block profile does not respect the operating constraints of the associated thermal generating unit (i.e., start-up process and desynchronization process) and is not flexible enough to adjust to the hourly load requirements.

Note that the THOs could be an additional possibility to the block orders, or they could entirely replace the block orders in the European market clearing algorithm. Consider the following example: a participant submits a block order with $Q_{bo,t}=100$ MWh/h for 7 hours. The minimum acceptance ratio is $AR_{bo}^{\min}=0.6$. This means that the block order can be accepted for any quantity between 60 MWh/h and 100 MWh/h. The accepted quantity will be the same for all hours, since $Q_{bo,t}$ is the same and the acceptance ratio is common for all hours. Alternatively, the participant may submit a THO with the maximum quantity $Q_{tho,t}^{\max}=100$ MWh and the minimum quantity $Q_{tho,t}^{\min}=60$ MWh for the same 7 hours. The minimum up time of this order is $UT_{tho}^{\min}=7$ hours; thus, this order will be either accepted for the full 7 hours or rejected in its entirety (similar to the block order). Additionally, the synchronization, start-up, and shut-down time of this order may be set to be zero $T_{tho}^{syn}=T_{tho}^{su}=T_{tho}^{sd}=0$ and the start-up profile $Q_{tho,f}^{su}$ can be left empty. This means that the order will not follow the different operating trajectories of thermal unit (similar to the block order). The only difference between the block order and the THO in this case is that the accepted quantity for any given hour may be different for the THO while it will be the same for the block order. This means that the THO provides a wider solution space to the algorithm, which can lead to its acceptance in cases where an equivalent block order would have been rejected. Finally, a common acceptance ratio could be introduced for the THO as well, with the possibility to be activated by the user or not. In this case, all block order features are simulated by the THO, and thus the THOs could fully replace the block orders to minimize complexity.

Additionally, the indivisible character of the block orders produces more frequent jumps in the MCPs from hour to hour, as shown in Fig. 6 for the Greek bidding zone.

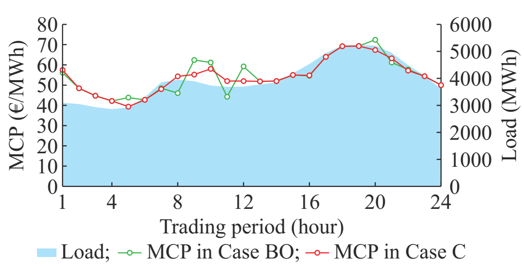

Fig. 6. MCPs in Greek bidding zone.

Another THO is presented in Fig. 5(b). The THO (THO2) is in desynchronization status at the start of the trading horizon (see Cases A and C). Thus, in the successive minimum down time hours, the order is not cleared. When the demand becomes higher (after hour 9), the order is activated again following a detailed start-up process. The same clearing results are attained in both Cases A and C, meaning that the order fulfills its MIC from the first iteration of the algorithm.

C. Clearing of DROs and ELOs

Figure 7 presents a typical example of the DRO clearing in France (FR) bidding zone. In both Cases A and C, this order is cleared in the trading periods of hours 8-11 and 19-22, where the system demand and the market prices are higher. The order has a maximum frequency of activations equal to 2, and thus it is cleared only two times during the trading day. Additionally, it has a maximum delivery period of 4 hours, and thus it is cleared only for four consecutive hours each time. A user-defined minimum baseload period of 7 hours is also satisfied (the order is inactive between hours 12 and 18). The order is cleared in Case C since the attained market revenue is higher than the required revenue (the MCP during the clearing hours is higher than the variable term of the order).

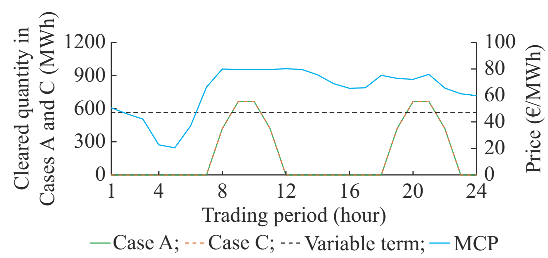

Fig. 7. Typical example of DRO clearing.

Figure 8 presents a typical example of the ELO clearing in Great Britain (GB) bidding zone. Energy is stored during low-price hours 1-7, so that it can be later used for peak clipping (discharging in hours 11-13 and 18-20). The order is cleared in both Cases A and C since its MIC is fulfilled in all iterations of the algorithm.

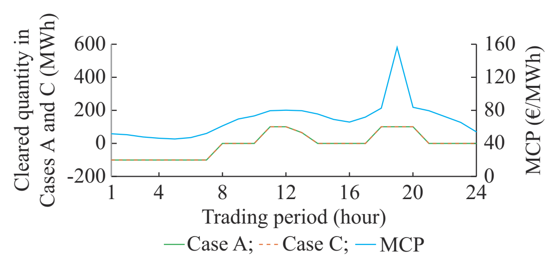

Fig. 8. Typical example of ELO clearing.

D. Discussion on Pricing Schemes

Both Cases A and C ensure economic non-confiscation for the sellers since they compensate for the entirety of the sellers' costs. In Case A, side-payments are calculated ex-post as the difference between the required revenues of participants and the attained revenues in the first iteration of the algorithm. In this paragraph, a comparison is performed between Cases A and C in terms of social welfare, derived revenues of the sellers, and robustness of the attained results.

Table II presents the social welfare, removed orders, and execution time of each iteration of the algorithm. Note that the magnitude of the social welfare is quite higher than the revenues of sellers (market revenues) as presented in Table III. This is driven by the inelastic demand priced at 1000 €/MWh in this case study. The PAOs removed at the end of each iteration are shown in the 3rd column of Table II. The number of eligible orders (i.e., the orders satisfying the condition $V_o^{ratio} \leq 0.1$, which are provided an additional opportunity to be cleared during the next iteration) is presented in the following four columns. The number of removed orders (for which $V_o^{ratio} > 0.1$) is presented right after. The eligibility threshold is $X = 10\%$ and the number of opportunities for the orders bearing an MIC is $Y = 3$. The execution time per iteration is presented in the last column. The overall execution time respects the European standard (less than 0 min [4]), but the model complexity could be assessed in the presence of a higher number of orders compared to this case study. No warm starting has been utilized between the various iterations, which could potentially decrease further the overall execution time.

TABLE II
SOCIAL WELFARE, REMOVED ORDERS, AND EXECUTION TIME

Iteration	Social welfare (M€)	PAOs removed	Number of eligible order ($V_o^{ratio} \leq 0.1$)				Number of removed order ($V_o^{ratio} > 0.1$)				Execution time (s)
			Supply order	THO	DRO	ELO	Supply order	THO	DRO	ELO	
1	5792.997	6	1	3	7	39	5	2	12	35	34.03
2	5792.902	1	1	4	7	39	2	0	0	0	32.94
3	5792.899	0	1	4	7	39	2	0	0	0	32.89
4	5792.722	3	0	1	0	0	2	0	0	0	31.78
5	5792.717	2	0	1	0	0	1	0	0	0	31.94
6	5792.715	4	0	1	0	0	0	0	0	0	32.01
7	5792.717	1	0	1	0	0	0	0	0	0	31.54
8	5792.716	2	0	1	0	0	0	0	0	0	33.41
9	5792.717	0	0	0	0	0	0	1	0	0	32.50
10	5792.716	0	0	0	0	0	0	0	0	0	31.53

As shown in Table II, ten iterations are needed to clear all PAOs and the orders not satisfying their MIC. After the last iteration, there are neither PAOs nor orders not fulfilling their MIC, and the algorithm terminates. The social welfare mainly decreases in the successive iterations, since the orders maximizing the objective but failing to respect the imposed revenue criteria are successively removed from the market solution. The social welfare is higher in Case A (the 1st iteration in Table II), where the aforementioned orders are retained in the final market solution and are compensated through ex-post side-payments.

Table III provides the market revenues, side-payments, and total revenues of sellers in each iteration of the algorithm.

TABLE III
MARKET REVENUES, SIDE-PAYMENTS, AND TOTAL REVENUES

Iteration	Market revenue (M€)	Side-payment (M€)	Total revenue (M€)
1 (Case A)	376.057	0.136	376.193
2	376.459	0.013	376.472
3	376.524	0.021	376.545
4	376.773	0.016	376.789
5	376.941	0.008	376.949
6	376.770	0.001	376.771
7	376.904	0	376.904
8	376.878	0	376.878
9	376.943	0.004	376.947
10 (Case C)	376.940	0	376.940

The figures in the first row correspond to Case A. The direct revenue of sellers from the DAM in Case A is 376.057 M€ in total, whereas the side-payments amount to 0.136 M€. The total revenues in Case A amount to 376.193 M€, thus the side-payments represent only 0.036%. In Case C (last iteration), there are no side-payments. The total revenue of sellers reach 376.940 M€, which is higher than that in Case A by 0.747 M€ (0.198%). This is because the iterative process of Case C leads to the exclusion of several PAOs and orders not fulfilling their MIC, thereby incurring an increase in MCPs which outweighs the side-payments of Case A. Overall, Case A leads to lower costs for the end-consumers.

Finally, Fig. 9 provides insights on the robustness of the attained solution in Case C. A sensitivity analysis is performed on how the values of parameters X (i.e., eligibility threshold for MIC orders) and Y (i.e., the number of opportunities provided to MIC orders to be cleared in next iterations) change the number of required iterations for convergence and the social welfare. In Fig. 9(a), $Y = 3$, and the sensitivity analysis is performed for parameter X, while in Fig. 9(b), $X = 10\%$, and the sensitivity analusis is performed for parameter Y. As observed, the values selected for both X and Y considerably change the social welfare. The number of required iterations is also affected, with a generally increasing trend as X and Y increase. This solution instability, both in terms of social welfare (volumes and prices) and iterations, is a weak feature of Case C followed by most European DAMs for rendering the market non-confiscatory. In opposite, Case A does not require an iterative process; the cleared volumes and the respective prices are globally optimal and more transparent.

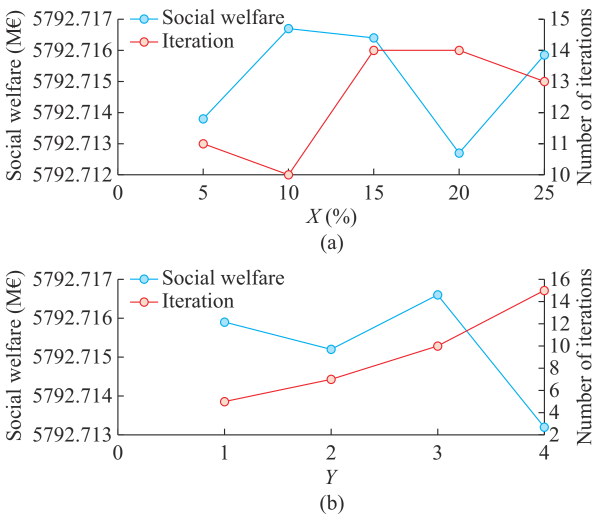

Fig. 9. Sensitivity analysis on eligibility threshold X and number of opportunities Y in Case C. (a) X. (b) Y.

IV. Conclusion

This paper addresses two main issues that concern the market participants in European DAMs, namely the feasibility of the attained schedules and the non-confiscation of the cleared volumes.

In order to address the first issue, resource-specific orders have been developed, i.e., THOs, DROs, and ELOs. The enhanced scheduling of the resources when using the new order types has been identified in the results. While the block orders do not always respect the operating constraints of a thermal generating unit and they are not flexible enough to adjust to the hourly load requirements, the proposed THOs provide for a typical start-up/normal dispatch/desynchronization process, respecting other thermal unit constraints such as the minimum up/down time. Regarding the DROs, it is shown that main operating constraints are satisfied, such as a minimum and a maximum delivery period, a minimum baseload period, or a given frequency of activations in the course of a day. Similarly, the results show that the ELOs respect the discharging/charging capability of a storage asset, the state of charge constraints, and the total discharging/charging limitation within a trading day. In that respect, the European legislation should promote the introduction of resource-specific orders in the DAM clearing of the internal electricity market. Notably, the computational complexity of the benchmark European DAM model in the presence of the new order types has been assessed, and the execution time is within the European standards.

To address the second issue, a comparative analysis has been performed between two pricing schemes that ensure non-confiscation: discriminatory pricing with side-payments and non-discriminatory pricing excluding out-of-money orders (the prevalent scheme in European markets). The results indicate that the former scheme exhibits certain advantages: ① the derived revenues of the sellers, which shall be borne by the buyers and eventually by the end-consumers, are lower; ② the make-whole payments to the sellers represent a small portion of their total revenues; ③ no iterative process employing revenue-constrained controls is required (as in the second pricing scheme), thereby the market solution is more stable in terms of cleared volumes and prices.

Future research will investigate and compare the above two pricing schemes with the case of non-discriminatory pricing, where uplift payments are directly included in the market clearing. Convex hull pricing and extended locational marginal pricing shall be investigated to reduce side-payments. Additionally, THOs shall be introduced in more bidding zones to assess the computational burden. Finally, the approach will be tested with a flow-based transportation model (c. f. ATC-based model used in this paper), which is gradually being implemented in the European region.

Appendix A

Let L be the Lagrange function of the optimization problem (1) - (45). At optimality, the Karush-Kuhn-Tucker conditions yield:

$$\frac{\partial L}{\partial p_{z,t}} = 0 \tag{A1}$$

By further processing (A1), we get:

$$\frac{\partial L}{\partial p_{z,t}} = 0 \Rightarrow \frac{\mathrm{d}F}{\mathrm{d}p_{z,t}} - \lambda_{z,t} + (\mu^{up}_{z,t} - \mu^{up}_{z,t+1}) - (\mu^{dn}_{z,t} - \mu^{dn}_{z,t+1}) = 0 \Rightarrow \pi_{z,t} = \frac{\mathrm{d}F}{\mathrm{d}p_{z,t}} = \lambda_{z,t} - (\mu^{up}_{z,t} - \mu^{up}_{z,t+1}) + (\mu^{dn}_{z,t} - \mu^{dn}_{z,t+1}) \tag{A2}$$

References

[1] Directive 2009/72/EC of the European Parliament and of the Council of 13 July 2009 concerning common rules for the internal market in electricity and repealing Directive 2003/54/EC, 2009.

[2] Commission Regulation (EU) 2015/1222 of 24 July 2015 establishing a guideline on capacity allocation and congestion management, 2015.

[3] EPEX SPOT. (2022, Aug.). European market coupling. [Online]. Available: https://bit.ly/3wrSYuC

[4] NEMO Committee. (2022, Aug.). EUPHEMIA public description, 2020. [Online]. Available: https://bit.ly/3qm1yaz

[5] Price Coupling of Regions. (2022, Aug.). Euphemia performance, 2015. [Online]. Available: https://bit.ly/3u5zXvo

[6] European Commission. (2022, Aug.). Clean energy for all Europeans package. [Online]. Available: https://bit.ly/3JpG3gF

[7] European Commission. (2022, Aug.). Study on energy storage–contribution to the security of the electricity supply in Europe. [Online]. Available: https://bit.ly/3CROqz0

[8] ENTSO-E. (2015, Nov.). Market design for demand side response, policy paper. [Online]. Available: https://bit.ly/3Ihu6s0

[9] C. Batlle, I. Herrero, and P. Rodilla, "Evolving bidding formats and pricing schemes in USA and Europe day-ahead electricity markets," *Energies*, vol. 13, pp. 1-21, Sept. 2020.

[10] EPEX SPOT. (2022, Aug.). EPEX SPOT introduces curtailable blocks and loop blocks on all day-ahead markets. [Online]. Available: https://bit.ly/3N3mvAV

[11] G. Liberopoulos and P. Andrianesis, "Critical review of pricing schemes in markets with non-convex costs," *Operation Research*, vol. 64, no. 1, pp. 17-31, Feb. 2016.

[12] B. Eldridge, R. O'Neill, and B. F. Hobbs, "Near-optimal scheduling in day-ahead markets: pricing models and payment redistribution bounds," *IEEE Transactions on Power Systems*, vol. 35, no. 3, pp. 1684-1694, May 2020.

[13] A. J. Conejo and R. Sioshansi, "Rethinking restructured electricity market design: lessons learned and future needs," *International Journal of Electrical Power & Energy*, vol. 98, pp. 520-530, Jun. 2018.

[14] S. Harvey. (2022, Aug.). Is the California ISO becoming an uplift market? Pricing, uplift and commitment (presentation), FTI consulting, 2014. [Online]. Available: https://bit.ly/36r10ZY

[15] Single Electricity Market Operator (SEM). (2021, Nov.). Trading and settlement code, Version 25.0. [Online]. Available: https://bit.ly/3qfonNi
[16] P. R. Gribik, W. W. Hogan, and S. L. Pope. (2007, Jul.). Market-clearing electricity prices and energy uplift. [Online]. Available: https://hepg. hks. harvard. edu/publications/market-clearing-electricity-prices-and-energy-uplift
[17] R. P. O'Neill, P. M. Sotkieqicz, and M. H. Rothkopf. (2007, Jul.). Equilibrium prices in power exchanges with non-convex bids. [Online]. Available: http://bear.warrington.ufl.edu/centers/purc/docs/papers/0601_ONeill_Equilibrium_Prices_in.pdf
[18] E. J. Zak, S. Ammari, and K. W. Cheung, "Modeling price-based decisions in advanced electricity markets," in *Proceedings of 2012 9th International Conference on the European Energy Market*, Florence, Italy, May 2012, pp. 1-6.
[19] NYISO. (2022, Aug.). Motion for permission to implement hybrid fixed block generation pricing rule. [Online]. Available: https://bit.ly/3IvQM88
[20] MISO. (2022, May). ELMP III White Paper I R&D report and design recommendation on short-term enhancements. [Online]. Available: https://bit.ly/3JnSyt5
[21] A. G. Vlachos and P. N. Biskas, "Balancing supply and demand under mixed pricing rules in multi-area electricity markets," *IEEE Transactions on Power Systems*, vol. 26, no. 3, pp. 1444-1453, Aug. 2011.
[22] L. Meeus, K. Verhaegen, and R. Belmans, "Block order restrictions in combinatorial electric energy auctions," *European Journal of Operational Research*, vol. 196, no. 3, pp. 1202-1206, Mar. 2009.
[23] C. Ruiz, A. Conejo, and S. Gabriel, "Pricing non-convexities in an electricity pool," *IEEE Transactions on Power Systems*, vol. 27, no. 3, pp. 1334-1342, Aug. 2012.
[24] I. Herrero, P. Rodilla, and C. Battle, "Electricity market-clearing prices and investment incentives: the role of pricing rules," *Energy Economics*, vol. 47, pp. 42-51, Jan. 2015.
[25] A. Martin, J. Müller, and S. Pokutta, "Strict linear prices in non-convex European day-ahead electricity markets," *Optimization Methods & Software*, vol. 29, no. 1, pp. 189-221, Jan. 2014.
[26] G. A. Dourbois and P. N. Biskas, "European market coupling algorithm incorporating clearing conditions of block and complex orders," in *Proceedings of 2015 IEEE Eindhoven PowerTech*, Eindhoven, Netherlands, Jul. 2015, pp. 1-6.
[27] A. G. Vlachos, G. A. Dourbois, and P. N. Biskas, "Comparison of two mathematical programming models for the solution of a convex portfolio-based European day-ahead electricity market," *Electric Power Systems Research*, vol. 141, pp. 313-324, Dec. 2016.
[28] D. I. Chatzigiannis, G. A. Dourbois, P. N. Biskas *et al*., "European day-ahead electricity market clearing model," *Electric Power Systems Research*, vol. 140, pp. 225-239, Nov. 2016.
[29] M. Madani and M. van Vyve, "A MIP framework for non-convex uniform price day-ahead electricity auctions," *EURO Journal on Computational Optimization*, vol. 5, pp. 263-284, Mar. 2017.
[30] R. P. O'Neill, A. Castillo, B. Eldridge *et al*., "Dual pricing algorithm in ISO markets," *IEEE Transactions on Power Systems*, vol. 32, no. 4, pp. 3308-3310, Jul. 2017.
[31] R. Fernández-Blanco, J. M. Arroyo, and N. Alguacil, "On the solution of revenue-and network-constrained day-ahead market clearing under marginal pricing – Part I: an exact bilevel programming approach," *IEEE Transactions on Power Systems*, vol. 32, no. 1, pp. 208-219, Jan. 2017.
[32] D. I. Chatzigiannis, P. N. Biskas, and G. A. Dourbois, "European-type electricity market clearing model incorporating PUN orders," *IEEE Transactions on Power Systems*, vol. 32, no. 1, pp. 261-273, Jan. 2017.
[33] A. Sleisz and D. Raisz, "Integrated mathematical model for uniform purchase prices on multi-zonal power exchanges," *Electric Power Systems Research*, vol. 147, pp. 10-21, Jun. 2017.
[34] I. Savelli, A. Giannitrapani, S. Paoletti *et al*., "Introducing block orders in the Italian day-ahead electricity market," in *Proceedings of 2018 15th International Conference on the European Energy Market*, Lodz, Poland, Jun. 2018, pp. 1-6.
[35] I. Savelli, A. Giannitrapani, S. Paoletti *et al*., "An optimization model for the electricity market clearing problem with uniform purchase price and zonal selling prices," *IEEE Transactions on Power Systems*, vol. 33, no. 3, pp. 2864-2873, May 2018.
[36] I. Savelli, B. Cornélusse, A. Giannitrapani *et al*., "A new approach to electricity market clearing with uniform purchase price and curtailable block orders," *Applied Energy*, vol. 226, pp. 618-630, Sept. 2018.
[37] L. H. Lam, V. Ilea, and C. Bovo, "European day-ahead electricity market coupling: discussion, modeling, and case study," *Electric Power Systems Research*, vol. 155, pp. 80-92, Feb. 2018.
[38] G. A. Dourbois, P. N. Biskas, and D. I. Chatzigiannis, "Novel approaches for the clearing of the European day-ahead electricity market," *IEEE Transactions on Power Systems*, vol. 33, no. 6, pp. 5820-5831, Nov. 2018.
[39] N. Koltsakis and A. Dagoumas, "Incorporating unit commitment aspects to the European electricity markets algorithm: an optimization model for the joint clearing of energy and reserve markets," *Applied Energy*, vol. 231, pp. 235-258, Sept. 2018.
[40] N. Koltsakis and A. Dagoumas, "Policy implications of power exchanges on operational scheduling: evaluating EUPHEMIA's market products in case of Greece," *Energies*, vol. 11, pp. 1-26, Oct. 2018.
[41] A. Sleisz, D. Divényi, and D. Raisz, "New formulation of power plants' general complex orders on European electricity markets," *Electric Power Systems Research*, vol. 169, pp. 229-240, Apr. 2019.
[42] Nord Pool. (2022, Aug.). Ramping. [Online]. Available: https://bit.ly/3JqXFc0
[43] R. P. O'Neill, P. M. Sotkiewicz, B. F. Hobbs *et al*., "Efficient market-clearing prices in markets with non-convexities," *European Journal of Operational Research*, vol. 164, pp. 269-285, Jul. 2005.
[44] ENTSO-E. (2022, Mar.). Transparency platform. (2022, Aug.). [Online]. Available: https://bit.ly/3EbP50U
[45] I. G. Marneris, A. V. Ntomaris, P. N. Biskas *et al*. TestCase. [Online]. Available: https://bit.ly/3KWfGiH
[46] Hellenic Energy Exchange. (2022, Aug.). Market data & publications. [Online]. Available: https://bit.ly/3RMPkCZ

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