Recovery Mechanisms in a Joint Energy/Reserve Day-Ahead Electricity Market with Non-Convexities

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***Abstract*--The goal of this paper is to evaluate the incentive compatibility of several cost- and bid-based recovery mechanisms that may be implemented in a wholesale electricity market to make the generation units whole in the presence of non-convexities, which are due to unit commitment costs and capacity constraints. To this end, we simulate the bidding behavior of the participants in a simplified model of the Greek joint energy/reserve day-ahead electricity market, where we assume that the players (units) participate as potential price-makers in a non-cooperative game with complete information that is repeated for many rounds. The results suggest that a mechanism based on bid recovery with a regulated cap is quite promising.**

***Index Terms*—Electricity market modeling and simulation, recovery mechanisms**

I. NOMENCLATURE

A. Sets - Indices

U	Generation units, indexed by u
u	Generation unit index: $u\in U$
h	Hour (time period) index: $h\in\{0,1,\ldots,H\}$

B. Parameters

$P^g_{u,h}$	Price of energy offer for unit u, hour h
$P^r_{u,h}$	Price of reserve offer for unit u, hour h
NLC_u	No-load cost for unit u
SUC_u	Start-up cost for unit u
SDC_u	Shut-down cost for unit u
D_h	Demand (load) for hour h
R^{req}_h	Reserve requirement for hour h
$Q^{\min}_u$	Technical minimum for unit u
$Q^{\max}_u$	Technical maximum for unit u
$R^{\max}_u$	Maximum reserve availability for unit u
MU_u	Minimum uptime for unit u
MD_u	Minimum downtime for unit u
ST^0_u	Initial status of unit u (at hour 0)
X^0_u	Number of hours unit u has been "ON" at hour 0
W^0_u	Number of hours unit u has been "OFF" at hour 0
C^g_u	Cost of energy generation for unit u

C. Decision variables

$G_{u,h}$	Total generation (output) for unit u, hour h
$R_{u,h}$	Reserve included in DAS for unit u, hour h
$ST_{u,h}$	Status (condition) for unit u, hour h. Binary variable. 1: ON(LINE), 0:OFF(LINE)
$Y_{u,h}$	Startup signal for unit u in hour h. Dependent binary variable. 1: Start-up, 0: No start-up
$V_{u,h}$	Shutdown signal for unit u in hour h. Dependent binary variable. 1: Shut-down, 0: No shut-down
$X_{u,h}$	Number of hours unit u has been ON at hour h since last start-up. Integer variable
$W_{u,h}$	Number of hours unit u has been OFF at hour h since last shut-down. Integer variable

II. INTRODUCTION

THIS paper considers the design of a joint energy/reserve, day-ahead electricity market with non-convexities. The market model is formulated as a *Mixed Integer Linear Programming* (MILP) problem that is solved every day, simultaneously for all 24 hours of the next day. The solution determines the unit commitment and the clearing of all the market commodities, namely energy and reserves. With the term "reserves" we refer to the frequency-related ancillary services. The non-convexities are due to the commitment costs and capacity constraints of the generation units. All commodities are priced using a uniform, marginal pricing scheme. The revenues from participating in such a market mechanism are not always sufficient to cover the costs of the generation units. Therefore, a recovery mechanism is needed to compensate the generation units and make them whole.

Non-convexities as a feature of electricity markets have been addressed in [1]-[5]. O' Neill et al. [1] model a market with indivisibilities as an MILP problem, and then use its optimal solution to create a *Linear Programming* (LP) problem by expanding the set of commodities to include any activities that are associated with the integer variables. Hogan and Ring [2] consider the unit commitment problem for a day-ahead electricity market and present a minimum-uplift pricing

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approach that focuses on non-convexities, taking into account the generation units' technical minimum and maximum constraints and start-up costs. Bjørndal and Jörnsten [3] address the same problem, and propose a methodology which is based on the generation of a separating valid inequality that supports optimal resource allocation. Gribik et al. [4] consider alternative ways of defining uniform energy prices, and calculate the associated impact on the energy uplift required to support the least-cost unit commitment and dispatch. Andrianesis et al. [5] describe a bid recovery mechanism, based on the analysis in [1], that applies to the day-ahead market problem and propose a simulation-based methodology to evaluate its incentive compatibility.

In this paper, we use the methodology proposed in [5] to evaluate the incentive compatibility of several different recovery mechanism designs that are based on either cost or bid recovery schemes. The main contribution of this work is the insights that we gain concerning the behavior of the market participants under each design.

The remainder of this paper is organized as follows. First, we present the model of the joint energy/reserve day-ahead market problem, and we describe the recovery mechanism designs under consideration. Then, we sketch the simulation-based methodology for evaluating the bidding behavior of the generation units under each design, and we apply this methodology on an example representing the Greek energy market. Finally, we discuss the numerical results and draw conclusions.

III. Joint Energy/Reserve Day-Ahead Market Problem

The design of the joint energy/reserve, day-ahead electricity market that we consider is based on Greece's day-ahead market paradigm [6]. To keep our analysis focused we make several simplifying assumptions. Specifically, we focus only on thermal plants, and do not consider hydro plants, renewable energy sources, and imports/exports, as they are subject to different market rules and scheduling processes. Also, we consider only one type of reserve (tertiary spinning and non-spinning reserve); an extension to include all types (primary, secondary, and tertiary) is straightforward. The demand and reserve requirements are exogenously determined by the system operator and are adjusted to take into account the absence of energy injection from hydro plants, renewable energy sources, and net imports. The producers submit energy offers for each hour of the following day, as a stepwise function of price-quantity pairs, with successive prices being strictly non-decreasing. For simplicity, and without loss of generality, we assume a single price bid for energy. The producers also submit reserve bids as price-quantity pairs and start-up, shut-down, and no-load costs. The *Day-Ahead Scheduling* (DAS) problem can be formulated as a *Mixed Integer Programming* (MIP) problem as follows:

$$\min_{\substack{G_{u,h},R_{u,h}\\ ST_{u,h},Y_{u,h},V_{u,h}}} f_{DAS} = \sum_{u,h} P^g_{u,h}\cdot G_{u,h} + \sum_{u,h} P^r_{u,h}\cdot R_{u,h} + \sum_{u,h} ST_{u,h}\cdot NLC_u + \sum_{u,h} Y_{u,h}\cdot SUC_u + \sum_{u,h} V_{u,h}\cdot SDC_u \quad (1)$$

subject to: (shadow prices)

$$\sum_u G_{u,h} = D_h \quad \forall h \quad (p_h^G) \quad (2)$$

$$\sum_u R_{u,h} \ge R_h^{req} \quad \forall h \quad (p_h^R) \quad (3)$$

$$G_{u,h} - ST_{u,h}\cdot Q_u^{\min} \ge 0 \quad \forall u,h \quad (4)$$

$$-G_{u,h} - R_{u,h} + ST_{u,h}\cdot Q_u^{\max} \ge 0 \quad \forall u,h \quad (5)$$

$$-R_{u,h} + ST_{u,h}\cdot R_u^{\max} \ge 0 \quad \forall u,h \quad (6)$$

$$(X_{u,h-1} - MU_u)(ST_{u,h-1} - ST_{u,h}) \ge 0 \quad \forall u,h \quad (7)$$

$$(W_{u,h-1} - MD_u)(ST_{u,h} - ST_{u,h-1}) \ge 0 \quad \forall u,h \quad (8)$$

$$Y_{u,h} = ST_{u,h}(1 - ST_{u,h-1}) \quad \forall u,h \quad (9)$$

$$V_{u,h} = ST_{u,h-1}(1 - ST_{u,h}) \quad \forall u,h \quad (10)$$

$$X_{u,h} = (X_{u,h-1} + 1)ST_{u,h} \quad \forall u,h \quad (11)$$

$$W_{u,h} = (W_{u,h-1} + 1)(1 - ST_{u,h}) \quad \forall u,h \quad (12)$$

$$ST_{u,0} = ST_u^0 \quad \forall u \quad (13)$$

$$X_{u,0} = X_u^0 \quad \forall u \quad (14)$$

$$W_{u,0} = W_u^0 \quad \forall u \quad (15)$$

with $G_{u,h}, R_{u,h} \ge 0$, $ST_{u,h}, Y_{u,h}, V_{u,h}$ binary, and $X_{u,h}, W_{u,h}$ integer, $\forall u,h$.

The objective function (1) minimizes the cost of providing energy and reserve as well as other commitment costs (start-up, shut-down, and no-load cost). Constraints (2) and (3) represent the market clearing constraints, i.e., the energy balance and the reserve requirements. Constraints (4)-(8) represent the generation units' technical constraints (technical minimum/maximum, reserve availability, minimum up/down-time). Equalities (9)-(12) define the binary and integer variables, namely the start-up/shut-down signals, and time counters of hours that a unit has been online/offline. Equalities (13)-(15) state the initial conditions of the units. We replace the nonlinearities in constraints (9)-(12) with linear inequalities, introducing auxiliary variables wherever necessary [5], thus obtaining an MILP problem. We then solve the MILP problem and fix the integer variables at their optimal values (marked with an asterisk) to calculate the clearing prices. This leads to an LP problem in which constraints (7)-(15) have been replaced with the following equalities:

$$ST_{u,h} = ST^*_{u,h} \quad \forall u,h \quad (16)$$

$$Y_{u,h} = Y^*_{u,h} \quad \forall u,h \quad (17)$$

$$V_{u,h} = V^*_{u,h} \quad \forall u,h \quad (18)$$

Based on marginal pricing theory [7], the energy and reserve commodities are paid at the shadow price of the market clearing constraints (2) and (3), p_h^G and p_h^R, respectively.

IV. Recovery Mechanisms

In this section, we describe several different recovery mechanism designs and comment on their possible pros and cons. To further simplify the analysis, we assume that the cost for providing reserve is zero, the reserve offers are zero-priced, and the commitment costs are auditable. Consequently, the only decision variable for each generation unit is the single price of the energy offer.

A. No Recovery

First, let us consider the case where there is *no recovery mechanism*. In this case, the *revenues* (REVs_u) for the generation units consist of the energy and reserve payments, and the *total costs* (TCs_u) consist of the *variable costs* (VCs_u) for generating energy and the *commitment costs* (CCs_u). The profits (PROFs_u) are equal to the revenues minus the total costs and can be negative. More specifically:

$$\text{PROFs}_u = \text{REVs}_u - \text{TCs}_u = \text{REVs}_u - (\text{VCs}_u + \text{CCs}_u) \quad (19)$$

$$\text{REVs}_u = \sum_h p_h^G \cdot G_{u,h} + \sum_h p_h^R \cdot R_{u,h} \quad (20)$$

$$\text{VCs}_u = \sum_h C_u^g \cdot G_{u,h} \quad (21)$$

$$\text{CCs}_u = \sum_h ST_{u,h} \cdot NLC_u + \sum_h Y_{u,h} \cdot SUC_u + \sum_h V_{u,h} \cdot SDC_u \quad (22)$$

It is expected that for some units (e.g. for extra-marginal units) the revenues may not always cover both their variable and commitment costs. Thus, submitting truthful bids is likely to result in losses. But even with high bids, in some cases, it may still not be possible to recover the units' commitment costs, as high bids will result in units being extra-marginal (therefore in lower profits) or in shut-down instructions. In [1], [5] it is shown that, in general, a competitive equilibrium and efficient clearing prices in such a market model do not exist. Clearly, this design option is included here for completeness but in practical terms is not acceptable.

B. Cost-Based Recovery

Perhaps the simplest way to compensate the units in case they have losses from participating in the market is to implement a simple *cost-based recovery mechanism*. This means that if a unit does not recover its costs through its participation in the market, it will receive additional payments to cover its losses. Therefore, the profits will be:

$$\text{PROFs}_u = \max\{\, 0,\ \text{REVs}_u - \text{TCs}_u \,\} \quad (23)$$

The zero-profit condition above, however, may not be attractive. In fact, the behavior of the units under the cost recovery mechanism will be the same as that under the no recovery mechanism design option. Namely, the units will still try to maximize their profits (even if they are negative, in which case they will try to minimize their losses). The only difference is that under the cost recovery mechanism, units with negative profits will be made whole. Therefore, as far as the bidding behavior of the units is concerned, the outcome will still be the same, and the total payments will be increased by the amount of the payments for the recovery of the units with losses.

An alternative to the simple cost recovery mechanism is to always recover the commitment costs (CCs_u), thus eliminating a potential deficit due to this component. In addition, an extra compensation is to be given to the units that exhibit losses, even after the commitment costs recovery, so that these units will have a "reasonable" profit equal to a percentage, say α, of their variable cost. In this case, the profits will be:

$$\text{PROFs}_u = \begin{cases} \text{REVs}_u - \text{VCs}_u, & \text{if nonnegative} \\ \alpha \cdot \text{VCs}_u, & \text{otherwise} \end{cases} \quad (24)$$

Such a scheme, which we refer to as *variable cost-based recovery mechanism*, is used in the Greek market (with α = 5%), except that the additional compensation is given in an ex-post clearing market mechanism. In the following section, we will evaluate this recovery mechanism for α = 5%, and 10%. We expect, however, that such a mechanism will not discourage high bids, because the recovery is not directly associated with the bids; therefore, the mechanism may result in high prices and profits.

C. Bid-Based Recovery

Andrianesis et al. [5] propose a *bid recovery mechanism* based on the results of [1]. This mechanism allows the units that exhibit positive profits, calculated on a bid basis, to keep them, and compensates those that exhibit losses by fully recovering their *bids* (BIDs_u). In [5], it is shown that under this mechanism, the profits will be:

$$\text{PROFs}_u = \begin{cases} \text{BIDs}_u - \text{TCs}_u, & \text{if } \ \text{REVs}_u < \text{BIDs}_u \\ \text{REVs}_u - \text{TCs}_u, & \text{otherwise} \end{cases} \quad (25)$$

$$\text{BIDs}_u = \sum_h P_{u,h}^g \cdot G_{u,h} + \text{CCs}_u \quad (26)$$

In addition, it is shown that the application of such a mechanism in an oligopolistic market may result in particularly high and volatile prices. Units may take advantage of the mechanism and bid at very high prices, near the price cap.

To overcome this drawback, we propose to impose a regulated price cap that a unit has to respect in order to be eligible for bid recovery. If a unit exhibits profits on a bid basis, then no recovery is needed. If a unit exhibits losses (again on a bid basis), then it will be eligible for a bid recovery, provided that its bid lies between its variable cost and an upper bound (or regulated cap) which is equal to a fixed amount, say ε, over its variable cost, determined by the regulator. In other words, if $P_{u,h}^g \in [C_u^g, C_u^g + \varepsilon]$, then the unit is eligible for the bid recovery; else, the unit will receive no recovery. Under such mechanism, which we refer to as *regulated bid-based recovery mechanism*, the profits will be:

$$\text{PROFs}_u = \begin{cases} \text{BIDs}_u - \text{TCs}_u, & \text{if } \ \text{REVs}_u < \text{BIDs}_u \ \text{ and } P_{u,h}^g \le C_u^g + \varepsilon \\ \text{REVs}_u - \text{TCs}_u, & \text{otherwise} \end{cases} \quad (27)$$

The latter scheme can be considered as a mechanism design that motivates the bidder to behave rationally. Parameter ε can serve as a design parameter set by the regulator. A large value of ε will provide a strong incentive for the unit to bid within the recovery-eligibility margin, but may also result in large total payments; a low value, on the other hand, may not provide an adequate incentive and units may tend to bid above the upper bound. In the following section, we will evaluate this recovery mechanism for ε = 10, 8, 5, and 3 (€/MWh).

V. Game Description and Data

The key contribution of this paper is the development of a methodology that can be used to provide insights that each of the presented market design recovery options creates. This methodology is based on the simulation of the bidding behavior of the market participants under each market mechanism.

Due to the particularly complex nature of the optimization problem the analytical identification of a potential Nash equilibrium is practically impossible. For this reason, we assume that the players (units) participate as potential price makers in a non-cooperative game with complete information that is repeated for many rounds. In the first round, each player places a bid equal to its actual variable cost. In the next round, each player determines its bid as the price that maximizes its profits assuming that the other players' bids will remain unchanged. Since each player has the same objective of maximizing its profits, a new state of bids will be generated. We repeat this game for many rounds and we compare the outcomes for each recovery mechanism.

For the development of the methodology we use actual data from the Greek energy market. Specifically, the data represents an instance of Greece's electricity market and is listed in Tables I and II. This data is used as input to the DAS energy market clearing problem. Quantities are given in MW and prices for energy and reserve bids in €/MWh. The bids are considered to be the same for all 24 hours. Minimum uptimes/downtimes are given in hours and commitment costs in €. The minimum uptimes and the start-up costs are considered to be the same as the minimum downtimes and the shut-down costs, respectively. Initially, all units are considered to be online, so that they all have a common starting point. Values for counters that are not shown are given so that they will not affect the dispatching.

TABLE I
Units' Data (DAS Input)

Unit	Q_u^{max}	Q_u^{min}	R_u^{max}	C_u^g	MU_u	SUC_u	NLC_u	ST_u^0
U1	3800	2400	250	35	24	1 500 000	20 000	1
U2	377	240	137	49	3	13 000	500	1
U3	476	144	180	52	5	10 000	300	1
U4	550	155	180	55	5	25 000	350	1
U5	384	240	144	57	3	15 000	500	1
U6	151	65	45	64	16	18 000	150	1
U7	188	105	45	65	16	27 000	250	1
U8	287	120	10	70	8	50 000	600	1
U9	144	60	20	72	12	24 000	300	1
U10	141	0	141	150	0	5 000	200	1

TABLE II
Demand and Reserve Requirements

h	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
D_h	4200	3900	3800	3700	3700	3600	4000	4300	4800	5200	5550	5500
R_h^{req}	450	400	400	400	400	400	450	500	550	600	600	600
h	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**
D_h	5450	5450	5300	5000	4950	4900	5000	5200	5100	5000	4800	4500
R_h^{req}	600	600	600	550	550	550	550	600	600	550	500	500

Demand and reserve requirements data are adjusted to correspond only to the thermal plants that are available. Over thirty thermal units are installed in Greece's system. The lignite units serve as base units, and actual competition is mainly limited to the gas units. With this in mind, unit U1 is an aggregate representation of available lignite units. We assume that some units are not available due to scheduled maintenance or outages. Units U2, U3, U4 and U5 are combined cycle units, U6 and U7 are gas units, U8 and U9 are oil units, and U10 is a "peaker", i.e., a gas unit that can provide all its capacity for tertiary reserve. For the purposes of our analysis, we assume that all units, except U1 and U10, will participate in the game. Unit U1 will always have profits as it has the lowest cost, and unit U10 will have revenues mainly from the reserve market, since it will be the last unit to be dispatched for energy.

In case units submit equal bids, the tie-breaking rule that we use favors the unit with the lower variable cost. To achieve this, we make use of a small sorting parameter, ascending with cost by a small step (e.g. 10^{-4} or smaller) that is added at the energy offer price.

VI. Numerical Results

We modeled the DAS problem using the mathematical programming language AMPL [8] and solved it with the ILOG CPLEX 9.1 optimization commercial solver on a Pentium IV 1.8GHz dual core processor with 1GB system memory (integrality was assigned at zero and all other parameters were set at their default values). The problem consists of 480 linear, 1000 general integer, 730 binary variables, and 6158 constraints.

We assumed that all units have the same behavior, i.e., they choose the price offer that will maximize their profits for the next day. Among multiple price offers that generate equal profits, we applied a rule according to which they will choose to bid at the lowest price (risk-averse strategy). We used a relatively big step of 1 (€/MWh) while exploring the set of prices from the cost to the price cap, which was set at 150 €.

Some computational results are shown in Table III. In the case of the regulated bid recovery mechanism, we observed cycling in the bidding behavior. This is due to the discrete nature of the problem, since the bids take values from a finite set of prices. Such behavior is expected to occur with certainty in all cases if the number of rounds is larger than the number of possible states.

TABLE III
Computational Results

Mechanism	Rounds	Problems Solved	Aver. Sol. Time per problem (s)	Cycles	Period of Cycle
No Recovery	60	43501	4.073	NO	-
Cost Recovery	60	43501	4.073	NO	-
5% Var. Cost	30	21751	4.828	NO	-
10% Var. Cost	30	21751	4.699	NO	-
Bid Recovery	30	21751	7.531	NO	-
R. Bid Rec. (ε = 10)	30	21751	4.257	YES	2
R. Bid Rec. (ε = 8)	30	21751	4.101	YES	11
R. Bid Rec. (ε = 5)	30	21751	3.948	YES	8
R. Bid Rec. (ε = 3)	60	43501	3.758	YES	29

In Tables IV – VI, we present some of the more interesting numerical results for the different recovery mechanisms.

TABLE IV
NUMERICAL RESULTS

Mechanism	Average Surplus (€)	Average Total Uplift (€/MWh)	Average Anc.Serv. Uplift (€/MWh)	Average (%) of Cost Increase	Average (%) Surplus/ Cost
No Recovery	1 356 579	0.739	0.739	0.60	26.28
Cost Recovery	1 487 719	1.900	0.739	0.60	28.83
V. Cost (α=5%)	3 348 049	7.902	1.539	1.67	64.16
V. Cost (α=10%)	2 993 892	7.932	1.307	1.70	54.37
Bid Recovery	5 209 856	4.710	1.475	1.27	100.21
R. Bid Rec. (ε=10)	1 465 837	2.687	0.377	0.13	28.55
R. Bid Rec. (ε=8)	1 382 076	2.389	0.489	0.16	26.91
R. Bid Rec. (ε=5)	1 205 174	2.237	0.361	0.24	23.45
R. Bid Rec. (ε=3)	1 266 600	2.016	0.473	0.32	24.63
Reference Case	860 149	2.101	0.430	0.00	16.78

TABLE V
UNITS' PROFITS UNDER DIFFERENT RECOVERY MECHANISMS

Unit	No Recovery	Cost Recovery	V. Cost. (α = 5%)	V. Cost (α = 10%)	Bid Recovery
U1	1 329 623	1 329 623	2 740 560	2 478 993	3 909 760
U2	47 244	48 188	158 121	136 401	241 041
U3	57 692	57 835	113 098	104 659	256 977
U4	23 310	26 654	101 354	68 324	246 372
U5	-2 684	8 507	106 542	91 438	179 841
U6	-9 450	1 339	21 990	19 986	87 097
U7	-25 769	326	26 342	24 652	82 198
U8	-51 310	144	26 729	22 739	115 289
U9	-27 148	3	10 684	10 389	54 388
U10	15 071	15 095	42 624	36 307	36 889

TABLE VI
UNITS' PROFITS UNDER DIFFERENT RECOVERY MECHANISMS (CONT.)

Unit	Regulated Bid Recovery			
	ε = 3	ε = 5	ε = 8	ε = 10
U1	1 153 344	1 087 025	1 207 545	1 245 200
U2	33 232	30265	36 961	53 090
U3	40 030	29 577	47 759	54 177
U4	6 333	14 671	35 062	50 580
U5	11 356	16 890	17 454	23 760
U6	5 321	8 551	13 709	16 830
U7	1 819	2 215	3 999	5 813
U8	6 849	8 783	7 948	8 585
U9	538	2 352	3 346	2 520
U10	7 773	4 841	8 287	5 281

The averages are calculated for the total number of rounds, except for the case of the regulated bid-based recovery mechanism in which they are calculated for the period of the cycle. The average surplus refers to the total producer surplus. The average total uplift is the additional impact on the energy price of the combined payments for implementing the recovery mechanism as well as meeting the reserve requirements. The latter component is presented separately as an average uplift for the provision of ancillary services, and is calculated from the payments for reserve at the reserve clearing price. The average percentage of cost increase reveals the degree of inefficient dispatching, and the average percentage of the producer surplus over cost provides a more comprehensive view of the absolute numbers for the average surplus. The reference case of the last row in Table IV shows the results for the case in which the units bid at their variable cost and are compensated if they incur losses.

Tables VII – VIII show the average bids for units U2 – U9. The figures in parentheses show the difference of the average bids from the variable costs.

TABLE VII
UNITS' AVERAGE BIDS UNDER DIFFERENT RECOVERY MECHANISMS

Unit	No Recovery	Cost Recovery	V. Cost. (α = 5%)	V. Cost (α = 10%)	Bid Recovery
U2	55.2 (6.2)	55.2 (6.2)	61 (12)	60 (11)	92 (43)
U3	61.5 (9.5)	61.5 (9.5)	99.7 (47.7)	95.7 (43.7)	100 (45)
U4	77.7 (22.7)	77.7 (22.7)	111.6 (56.6)	110.8 (55.8)	106.3 (51.3)
U5	63.6 (6.6)	63.6 (6.6)	68.6 (11.6)	64.2 (7.2)	103.8 (46.8)
U6	70.3 (6.3)	70.3 (6.3)	82.3 (18.3)	77 (13)	120.8 (56.8)
U7	72.1 (7.1)	72.1 (7.1)	72.4 (7.4)	72 (7)	125.2 (60.8)
U8	78.8 (8.8)	78.8 (8.8)	84.5 (14.5)	82 (12)	130.9 (60.9)
U9	81.4 (9.4)	81.4 (9.4)	82 (10)	79.9 (7.7)	131.5 (59.5)

TABLE VIII
UNITS' AVERAGE BIDS UNDER DIFFERENT RECOVERY MECHANISMS (CONT.)

Unit	Regulated Bid Recovery			
	ε = 3	ε = 5	ε = 8	ε = 10
U2	55.7 (6.7)	54.6 (5.6)	56.1 (7.1)	59 (10)
U3	57.4 (5.4)	58.5 (6.5)	57.4 (5.4)	59 (7)
U4	71.5 (16.5)	63.9 (8.9)	64.7 (9.7)	65 (10)
U5	59.9 (2.9)	61.8 (4.8)	63.6 (6.6)	66 (9)
U6	67 (3)	69 (4)	72 (8)	74 (10)
U7	67 (2)	67.6 (2.6)	69.8 (4.8)	72 (7)
U8	72.7 (2.7)	74.4 (4.4)	75.7 (3.7)	77.5 (7.5)
U9	74 (2)	76.3 (4.3)	78.2 (6.2)	78.5 (6.5)

From Tables V – VI, we observe that in the absence of a recovery mechanism, units U5 – U9 incur substantial losses. A cost recovery mechanism makes them whole in case of losses, but, with the exception of U5 and U6, results in low profits.

The producer surplus is high for the mechanisms that allow profits as a percentage of the variable cost, and becomes quite high (equal to cost) under the bid-based recovery mechanism. Note that the surplus is smaller when α = 10% than when α = 5%. This can be explained by the fact that the higher the profits from the recovery mechanism, the lower the incentive for units to bid high in order to achieve higher profits at a higher clearing price; however, this may not hold for higher values of α (it remains to be investigated in future research). Among the cost recovery mechanisms, the simple cost recovery mechanism seems to be the most attractive, but the units still compete with high bids and price spikes are observed in some rounds.

The results are more interesting in the case of the regulated bid-based recovery mechanism. Compared with the previous cases (except for the no recovery case), the average producer surplus is lower for all the values of ε that are examined. Surprisingly, the lowest surplus is achieved for ε = 5, and not for ε = 3, which is smaller. This can be explained by observing the bidding behavior of the players. The lower the regulated cap, i.e. the tighter the margin within which the units have to bid in order to be eligible for bid recovery, the lower the profits they can achieve by the recovery. Therefore, if the cap is very low, units tend to bid above the upper bound, seeking higher profits through a higher clearing price. These "violations" of the bidding margin are observed with very high frequency for ε = 3 for units U2 – U4, and become less frequent as the cap increases; they completely disappear when ε = 10. The results show that this mechanism is incentive compatible subject to a rational selection of the regulated price cap. The selection of the optimal value of this cap can be a design parameter for the market designer to induce units in "reasonable" bids that will result in "reasonable" profits.

VII. Concluding Remarks

The main contribution of this paper is that it sheds light into the market design of a wholesale electricity market with non-convexities considering the recovery mechanism as part of the design. We explored different recovery mechanisms and we proposed a mechanism that seems to be incentive compatible.

Due to space limitations, we were not able to present all the numerical results; additional results will be presented in an extended version of this paper. A number of issues that can play a significant role in the market outcome needs to be examined, mostly regarding the assumptions while exploring the bidding behavior of the market participants as well as the DAS model (for instance a zonal pricing scheme [9] would better describe the Greek market). Nevertheless, despite the simplifying assumptions, the findings of this paper suggest that a regulated bid recovery mechanism is quite promising.

VIII. Acknowledgment

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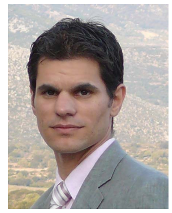
X. Biographies



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