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Soares, Tiago; Santos, Gabriel; Faria, Pedro; Pinto, Tiago; Vale, Zita; Morais, Hugo

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Integration in MASCEM of the Joint Dispatch of Energy and Reserves Provided by Generation and Demand Resources

Tiago Soares, Gabriel Santos, Pedro Faria, Tiago Pinto, Zita Vale
GECAD - Knowledge Engineering and Decision Support Research Center
IPP - Polytechnic Institute of Porto
Porto, Portugal
{tatso, gajls, pnfar, tmcfp, zav} @isep.ipp.pt

Hugo Morais
GECAD - Knowledge Engineering and Decision-Support Research Center / IPP - Polytechnic of Porto
Automation and Control Group / Technical University of Denmark (DTU)
Elektrovej build. 326, DK 2800 Kgs. Lyngby, Denmark
morais@elektro.dtu.dk

***Abstract*—The provision of reserves in power systems is of great importance in what concerns keeping an adequate and acceptable level of security and reliability. This need for reserves and the way they are defined and dispatched gain increasing importance in the present and future context of smart grids and electricity markets due to their inherent competitive environment. This paper concerns a methodology proposed by the authors, which aims to jointly and optimally dispatch both generation and demand response resources to provide the amounts of reserve required for the system operation. Virtual Power Players are especially important for the aggregation of small size demand response and generation resources. The proposed methodology has been implemented in MASCEM, a multi agent system also developed at the authors' research center for the simulation of electricity markets.**

***Index Terms*—Ancillary services, demand response, joint market simulation, multi agent systems, virtual power player.**

I. NOMENCLATURE

$buyer$	Buyer index
$C_{Buy(buyer,t)}$	Buyer *buyer* cost, for the energy product in period *t* [m.u./kWh]
$C_{Buy(vpp,t)}$	Buyer *vpp* cost, for the energy product in period *t* [m.u./kWh]
$C^{e}_{Sel(seller,t)}$	Seller *seller* cost, for the energy product in period *t* [m.u./kWh]
$C^{e}_{Sel(vpp,t)}$	Seller *vpp* cost, for the energy product in period *t* [m.u./kWh]
$C^{r}_{Sel(seller,t)}$	Seller *seller* cost, for the reserve product in period *t* [m.u./kWh]
$C^{r}_{Sel(vpp,t)}$	Seller *vpp* cost, for the reserve product in period *t* [m.u./kWh]
$Nbuyer$	Total number of buyers
$Nseller$	Total number of sellers
$Nvpp$	Total number of virtual power players
$P_{Buy(buyer,t)}$	*Buyer* scheduled demand power in period *t* [kW]
$P_{Buyer(vpp,t)}$	Buyer *vpp* scheduled demand power in period *t* [kW]
$P^{e}_{MaxSel(vpp,t)}$	Seller *vpp* maximum schedulable power, for the energy product in period *t* [kW]
$P^{e}_{MinSel(vpp,t)}$	Seller *vpp* minimum schedulable power, for the energy product in period *t* [kW]
$P^{e}_{Sel(seller,t)}$	Seller *seller* scheduled power, for the energy product in period *t* [kW]
$P^{e}_{Sel(vpp,t)}$	Seller *vpp* scheduled power, for the energy product in period *t* [kW]
$P_{MaxBuy(vpp,t)}$	Buyer *vpp* maximum schedulable power in period *t* [kW]
$P_{MaxSel(vpp,t)}$	Maximum power available from seller *vpp* in period *t* [kW]
$P_{MinBuy(vpp,t)}$	Buyer *vpp* minimum schedulable power in period *t* [kW]
pr	Reserve use probability
$P^{r}_{MaxSel(vpp,t)}$	Seller vpp maximum schedulable power, for the reserve product in period t [kW]
$P^{r}_{MinSel(vpp,t)}$	Seller vpp minimum schedulable power, for the reserve product in period t [kW]
$P^{r}_{Required(t)}$	Reserve product required power in period *t* [kW]
$P^{r}_{Sel(seller,t)}$	Seller *seller* scheduled power, for the reserve product in period *t* [kW]
$P^{r}_{Sel(vpp,t)}$	Seller *vpp* scheduled power, for the reserve product in period *t* [kW]
$seller$	Sellers index
t	Period index
T	Total number of periods
vpp	Virtual power players index
$X_{Buy(vpp,t)}$	Binary variable related to the use of buyer *vpp* in period *t*
$X^{e}_{Sel(vpp,t)}$	Binary variable related to the use of seller *vpp* for the energy product in period *t*
$X^{r}_{Sel(vpp,t)}$	Binary variable related to the use of seller *vpp* for the reserve product in period *t*

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II. INTRODUCTION

Several recent environmental and energetic concerns implemented through energy policies have caused an increase in the use of renewable energies based electricity generation. The generation units associated with those renewable energies are of small size, geographically dispersed, and usually referred as Distributed Generation (DG) [1].

The increasing integration of distributed generation at lower levels of power networks, namely at the level of distribution networks, has led to the implementation of the Smart Grid (SG) concept, which is being also associated with the use of Demand Response (DR) [2, 3].

Another important change in the operation and planning of power systems is the implementation of electricity markets. These competitive environments represent an opportunity for all the involved players to increase their and the whole system economic efficiency [4].

All the resources of all sizes, including the distributed generation and demand response, can participate directly in the electricity market in case of adequate resource size. For the resources of small size, not able to directly participate in the electricity market due to their physical characteristics but also to their reduced strategic capacity, Virtual Power Players (VPPs) assume a very relevant role enabling their participation in the electricity market [5]. These players aggregate both generation and consumption (including demand response and electric vehicles) resources [6].

In order to maintain increased levels of security required in the smart grid context, system reserves must give adequate attention to the intermittence and unpredictability of distributed generation and demand response resources availability.

The dispatch of resources providing energy and system reserves can be done in a joint or separate way. Focusing in the joint dispatch of energy and reserve, which is addressed in the present paper, the late and most relevant works, also including demand response resources, are presented in [7]-[9].

The methodology proposed in the present paper addresses the integration of the joint dispatch of energy and reserve in MASCEM [10, 11] simulator. Both DG and DR small size resources and consumers are able to be aggregated by one or several VPPs which participate in the market resources dispatch. The large size resources (generation, DR, and consumers) can participate directly in the dispatch as buyers (in the case of consumers and of consumption aggregators) or sellers (in the case of generators). The resources dispatch is formulated as an optimization problem which aims to minimize the operation costs. The model also considers the specified demand and reserve energy needs.

As referred, the proposed energy and Ancillary Services (AS) joint market model is incorporated into the MASCEM simulator. This integration provides the means for validating the proposed model through simulations based on real electricity markets' data in a well established and proof-given electricity market simulator. The MASCEM simulator is constantly under development and expansion since 2003 [10]. Throughout these years, MASCEM's model has accommodated a large number of different players and of electricity market types, using models from several countries. These include day-ahead models, forward contracts, balancing markets, complex markets and bilateral contracts. The integration of the energy and AS joint market also comes to expand the MASCEM capabilities in simulating as many market models extending the simulator functions.

The structure of the paper, after this introduction section, is as follows: Section III presents an overview of the MASCEM simulator, including the addition of the energy and AS joint market model in this simulator; Section IV presents the computational implementation of the problem, detailing the specificities of the proposed energy and reserve joint market; Section V illustrates the application of the proposed approach in a demonstrative case study; finally, Section VI exposes the most important conclusions of the work.

III. ANCILLARY SERVICES IN MASCEM

MASCEM [10, 11] is a simulator which aims to facilitate the study of complex electricity markets. Figure 1 presents the global structure of MASCEM, where consumers (C), producers (P), energy storage systems (St), electric vehicles (V2G) and VPPs are the players supported by MASCEM.

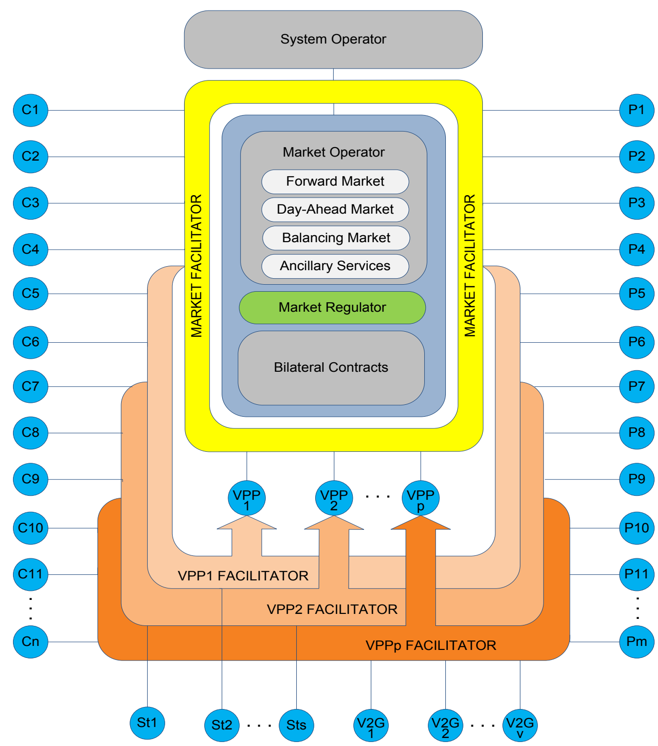

Figure 1. MASCEM's global structure [13].

MASCEM considers the main entities that are part of those markets, such as market players and operators, and intends to enable the simulation of the largest possible number of market models and types of players. Players can act in forward, day-ahead (symmetric and asymmetric) and balancing markets, considering both simple and complex bids. To guarantee competitive advantage in the market, players are also provided with bidding strategies [11], allowing them to achieve the best possible results in the market. MASCEM includes a market operator agent, an independent system operator agent (ISO), a market facilitator agent, buyer agents, seller agents, Virtual Power Player (VPP) [12] agents, and VPP facilitators.

The market operator validates and analyses the buyer and seller agents' bids according to the type of negotiation; it determines the market price, and the accepted and refused bids. The ISO is responsible for the system's security and for ensuring that all conditions are complied within the system. To do so, after being informed of all negotiations to be held, it examines the technical feasibility from the power system point of view and solves congestion problems that may arise.

The market facilitator knows all the market players, their roles and services, since they are registered in advance, and regulates all existing negotiations, coordinating and ensuring the proper operation of the market.

The key elements of the market are buyer and seller agents. The first ones may comprise for instance consumers and distribution companies, while the second ones may comprise electricity producers or other entities able to sell energy in the market.

Small independent players, such as small producers, mainly based on distributed generation and renewable sources, or consumers, need to make alliances between them in order to be able to compete in the market equally with big companies. These alliances are represented by VPPs [12, 14], which provide the adequate means to their aggregates, managing their information, and are seen from the market's standpoint as common buyers or seller agents. VPPs are modelled as a coalition of agents, allowing installing agents on separate machines, maintaining high computational performance. Such independence is achieved using VPP facilitators [12], which manage the communications between VPPs and their members independently from the rest of the simulation. VPPs send their bids to the MASCEM facilitator to participate in the electricity market.

MASCEM allows the simulation of the following markets: day-ahead pool (asymmetric or symmetric, with or without complex conditions), bilateral contracts, balancing market, forward markets and AS. The user determines for each agent whether to, and how to, participate in each market type. By selecting a combination of the market models mentioned above, hybrid simulations are also allowed.

The AS negotiation models implemented in MASCEM consider the most usual AS in a market environment (Regulation Down, Regulation Up, Spinning and Non-Spinning Reserve). Moreover, a simultaneous approach of energy and AS is considered in MASCEM [15].

The continuous development of the energy and AS joint market simulation model includes some differences in the market operation when compared to traditional AS models available in MASCEM. The main difference between the models lies in the agents bids. In the joint model, bids comprise simultaneously the energy and the ancillary services, as well as a global maximum limit of energy generation, which is independent from the maximum limits for each individual service. Thus, the model may allow greater benefits in operation costs from the ISO standpoint [15].

In addition to this model, this work includes the VPP dynamics in submitting bids to purchase and sell energy, including what concerns the sales in the reserve market. The energy and reserve bids of the large size sellers are also included. Furthermore, the model considers bids to purchase energy by retailers (buyers). In section IV all constraints and assumptions of the proposed methodology are detailed.

IV. Proposed Methodology

The proposed energy and reserve joint market can be modeled as an optimization problem that aims to minimize the operation costs in the market operator standpoint. The complexity of the proposed model leads to the formulation of a mixed-integer non-linear problem. The proposed optimization problem has been computationally implemented and solved in GAMS optimization tool [16].

In the proposed joint energy and reserve dispatch, which has been adapted from [9], the market operator receives bids from electricity buyers, electricity sellers, and VPPs for the provision of both energy and reserve requirements. VPPs can participate as a seller and/or as a buyer since these players can aggregate both generation and demand response resources, as well as consumption requirements. The objective function of the optimization problem, presented in equation (1) for each single period, considers the referred bids received from the players (buyers, sellers, and VPPs) for energy and reserve provision. The probability of using the reserve and the cost related to the non-contracted load shed are also included.

$$
\begin{aligned}
&Minimize\, OC = \\
&\sum_{vpp=1}^{Nvpp}\left[\begin{array}{l} P^{e}_{Sel(vpp,t)} \times C^{e}_{Sel(vpp,t)} + \\ \left[P^{r}_{Sel(vpp,t)} \times C^{r}_{Sel(vpp,t)}\right]\times pr \\ -P_{Buy(vpp,t)} \times C_{Buy(vpp,t)} \end{array}\right] + \\
&\sum_{seller=1}^{Nseller}\left[\begin{array}{l} P^{e}_{Sel(seller,t)} \times C^{e}_{Sel(seller,t)} + \\ \left[P^{r}_{Sel(seller,t)} \times C^{r}_{Sel(seller,t)}\right]\times pr \end{array}\right] - \\
&\sum_{buyer=1}^{Nbuyer} P_{Buy(buyer,t)} \times C_{Buy(buyer,t)}
\end{aligned}
\qquad (1)
$$

The amount of energy provided by the VPP in the market is constrained by its minimum and maximum limits for energy and reserve products. Furthermore, the total amount of energy available for both products is constrained by the VPP bid.

Equations (2) and (3) represent the minimum limit of energy that a VPP can deliver to the market for energy and reserve products respectively. Equations (4) and (5) represent the maximum limit of energy that a VPP can deliver to the market, for energy and reserve products respectively. Equation (6) concerns the total energy delivered in each period by the

VPP. The sum of energy and reserve products quantities must respect the maximum limit imposed by equation (6).

$$P^{e}_{Sel(vpp,t)} \geq P^{e}_{MinSel(vpp,t)} \times X^{e}_{Sel(vpp,t)} \quad (2)$$
$$\forall t \in \{1,...,T\}; \forall vpp \in \{1,..., Nvpp\}$$

$$P^{r}_{Sel(vpp,t)} \geq P^{r}_{MinSel(vpp,t)} \times X^{r}_{Sel(vpp,t)} \quad (3)$$
$$\forall t \in \{1,...,T\}; \forall vpp \in \{1,..., Nvpp\}$$

$$P^{e}_{Sel(vpp,t)} \leq P^{e}_{MaxSel(vpp,t)} \times X^{e}_{Sel(vpp,t)} \quad (4)$$
$$\forall t \in \{1,...,T\}; \forall vpp \in \{1,..., Nvpp\}$$

$$P^{r}_{Sel(vpp,t)} \leq P^{r}_{MaxSel(vpp,t)} \times X^{r}_{Sel(vpp,t)} \quad (5)$$
$$\forall t \in \{1,...,T\}; \forall vpp \in \{1,..., Nvpp\}$$

$$P^{e}_{Sel(vpp,t)} + P^{r}_{Sel(vpp,t)} \leq P_{MaxSel(vpp,t)} \quad (6)$$
$$\forall t \in \{1,...,T\}; \forall vpp \in \{1,..., Nvpp\}$$

The conditions imposed by equations (2) to (6) must be applied in the same way to each one of the considered large size sellers that participates in the market. In this way, each seller may submit bids for energy and reserve product respecting the referred constraints, which have been included in the model, but not detailed in this paper.

The binary variables used in these equations refer to the power dispatched for energy and reserve products. These variables are considered equal to 1 when a given player capacity is actually dispatched. Equations (12) and (13) regard, respectively, the minimum and maximum limits of the demand bids, i.e., the minimum and maximum power that can be dispatched for a specific player (VPP and/or buyer). In this way, the buyers share the same constraints used for the VPPs. Thus, equations (12) and (13) fit into the model applied to the buyers.

$$P_{Buy(vpp,t)} \geq P_{MinBuy(vpp,t)} \times X_{Buy(vpp,t)} \quad (12)$$
$$\forall t \in \{1,...,T\}; \forall vpp \in \{1,..., Nvpp\}$$

$$P_{Buy(vpp,t)} \leq P_{MaxBuy(vpp,t)} \times X_{Buy(vpp,t)} \quad (13)$$
$$\forall t \in \{1,...,T\}; \forall vpp \in \{1,..., Nvpp\}$$

In what concerns the balance equations of the problem, two distinct equations have been defined – one for energy (16) and another for reserve (17). The energy balance constraint, defined in equation (16), considers the VPPs and sellers bids for the energy product, and the VPPs and buyers demand bids to purchase energy. The reserve balance constraint, defined in equation (17), relates the power dispatched by each VPPs and sellers to fulfill the reserve requirement imposed by the system operator.

$$\sum_{vpp=1}^{Nvpp} P^{e}_{Sel(vpp,t)} + \sum_{seller=1}^{Nseller} P^{e}_{Sel(seller,t)} = \sum_{buyer=1}^{Nbuyer} P_{Buy(buyer,t)} + \sum_{vpp=1}^{Nvpp} P_{Buy(vpp,t)} \quad (16)$$
$$\forall t \in \{1,...,T\}$$

$$\sum_{vpp=1}^{Nvpp} P^{r}_{Sel(vpp,t)} + \sum_{seller=1}^{Nseller} P^{r}_{Sel(seller,t)} = P^{r}_{Required(t)} \quad (17)$$
$$\forall t \in \{1,...,T\}$$

V. Case Study

A case study which illustrates the implementation of the proposed methodology is presented in this section. The relevant information to the characterization of the problem is presented in Sub-section *A*. The results of the presented methodology are described in Sub-section *B*.

A. Case Characterization

The developed case study is based on a set of information of buying and selling bids to the energy and reserve joint market. The present case study regards a scenario developed for 24 single periods of one hour representing one day. The input data used in this case study have been adapted from the case study presented in [9] and it includes information related to a set of VPPs, and large size sellers and buyers. In what concerns the sellers information (both VPPs and large size sellers), the required data is presented in Table I. This includes information concerning the type of entity, the minimum and maximum global bid limit and global bid price for energy and reserve product (for each period, the minimum and maximum bid limits and prices vary according to the features of the entity) and the total capacity.

Several VPPs for supply energy and reserve are classified in accordance with the type of technology of its main resources (Photovoltaic, Combined Heat and Power – CHP, fuel cell, small hydro, wind, biomass and Municipal Solid Waste – MSW). In this way, there is a significant range of VPPs in which the predominant technology in its internal management is quite diversified from each other. In addition, there are two aggregators, classified as Curtailment Service Providers (CSP), which are entities able and dedicated to aggregate small size demand response resources. CSPs, similarly to VPPs, are able to participate in both energy and reserve market products. Five large size sellers are also considered in this scenario, with different power and price bids, able to participate in energy and reserve services.

From the buyers' perspective, the required information is presented in Table II. This table comprises similar information of the one presented in Table I, yet this time for three demand VPPs which only purchase energy, and one large size buyer.

TABLE I. SELLERS CHARACTERIZATION

Entities	Main technology	Minimum capacity (kW)		Maximum capacity (kW)		Total capacity (kW)	Minimum bid price (m.u./kWh)		Maximum bid price (m.u./kWh)	
		Energy	Reserve	Energy	Reserve		Energy	Reserve	Energy	Reserve
VPP1	Photovoltaic	-	-	352	150	502	0.14	0.15	0.19	0.21
VPP2	CHP	7	3	868	372	1240	0.022	0.24	0.022	0.24
VPP3	Fuel cell	7	3	165	70	235	0.1	0.11	0.1	0.11
VPP4	Hydro	21	9	49	21	70	0.03	0.04	0.05	0.06
VPP5	Wind	46	20	171	74	245	0.05	0.06	0.07	0.08
VPP6	Biomass	70	30	245	105	350	0.027	0.029	0.027	0.029
VPP7	MSW	7	3	7	3	10	0.028	0.033	0.061	0.062
Seller1	-	-	-	1275	225	1500	0.18	0.20	0.28	0.30
Seller2	-	-	-	1105	195	1300	0.19	0.24	0.26	0.29
Seller3	-	-	-	1190	210	1400	0.18	0.20	0.33	0.35
Seller4	-	-	-	1785	315	2100	0.21	0.15	0.29	0.17
Seller5	-	-	-	1062	188	1250	0.22	0.18	0.31	0.24
CSP1	-	11	5	759	505	1265	0.16	0.15	0.29	0.24
CSP2	-	5	2	241	161	402	0.23	0.15	0.38	0.18

TABLE II. BUYERS CHARACTERIZATION

Entities	Minimum capacity (kW)	Maximum capacity (kW)	Energy (m.u./kWh)
VPP8	-	675	0.42
VPP9	-	669	0.41
VPP10	-	315	0.40
Buyer1	3865	5102	0.45

The demand requirements have been defined for the 24 hours using the data presented in [17]. The base scenario considers a reserve requirement defined in 1000 kWh, in each period. The probability of using the reserve can vary between 0 and 1.

B. Results

The present sub-section presents the results of the application of the proposed methodology to the scenario detailed in the previous sub-section. The results obtained through the energy and reserve joint market simulation depend on the required reserve amount, on the probability of using the reserve, as well as on the variation of the resources prices that participate in the market. Regarding the probability of using the reserve, the market has been simulated according to the use of the reserve range between 0 and 1 with step 0.25. In order to evaluate the impact of the bids prices, a variation of this parameter value in the base scenario defined in sub-section A has been applied, only for large size sellers which are the players with higher influence in the results. A linear variation between 0.4 and 2, with step of 0.2 was simulated. In this simulation context, the graphs presented below were carefully selected to present all results obtained for this case study. Figure 2 shows the overall dispatch of all resources participating in the market. In Figure 2 it is presented the generation of all resources for both energy and reserve services. Regarding the required reserve amount, two distinct probabilities of using reserve are presented (0.5 corresponding to a) part of Figure 2 and 0.75 to b) part). The price variation of large size sellers was established in 0.6, 1.0 and 1.2. Moreover, Figure 2 illustrates the VPP buyer's results. The total costs that these VPPs acquire in the market for buying bids are presented in Figure 2. Through this figure, it can be concluded that the amount of energy dispatched by CSPs varies considerably with the prices of large size sellers bids. Thus, the share of CSPs in the dispatch is higher when the bid price of large size sellers is higher. Additionally, Figure 2 includes the Operation Costs (OC) related to each player (or set of players).

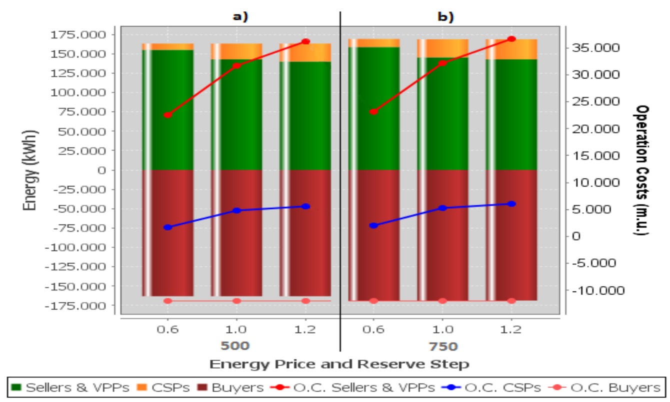

Figure 2. Operation costs and dispatched energy for both energy and reserve, for each player or set of players.

The energy dispatch for the 24-hour period is presented in Figure 3. In order to show these results it was considered the price step of the large size sellers equal to 1.0. These results are related to a probability of using the reserve equal to 0.5.

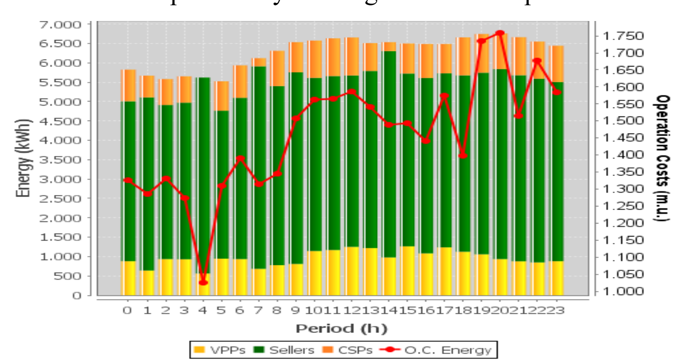

Figure 3. Operation costs and dispatched energy related to the energy product, for the 24 periods of the day.

The daily load profile diagram shows the sharing that VPPs and groups of large sizes sellers have in the energy product provision. In Figure 3 it is possible to see a considerable variation of the different resources over the simulation periods. This results in different bid limits that each resource offers in each period. In period 5, it seems that CSP resources do not contribute to the dispatch and VPPs contribute a little, while sellers are the main contributors. This is due to sellers' price being cheaper compared to other resources. On average, the large size sellers provide about 72.6% of the demand, while VPPs achieve 15.3% and CSPs contribute with the remaining 12.1%.

In what concerns the reserve dispatch, Figure 4 illustrates the share that each group of players has in the dispatch. These results (Figure 4) refer to the probability of using reserve established at 0.5, for the 24 periods of the day. Throughout the simulation periods, the VPPs group is the one which contributes more to the reserve (about 60.4%). This is due to the bid prices of the majority of the VPPs being the most competitive. The large size sellers contribute on average about 22.9%, followed by CSPs with about 16.7%. In some periods the sellers share is null (e.g. period 2), while in other periods the CSP share is null (e.g. period 24). This happens due to supply capacity and bid price in period to period vary substantially.

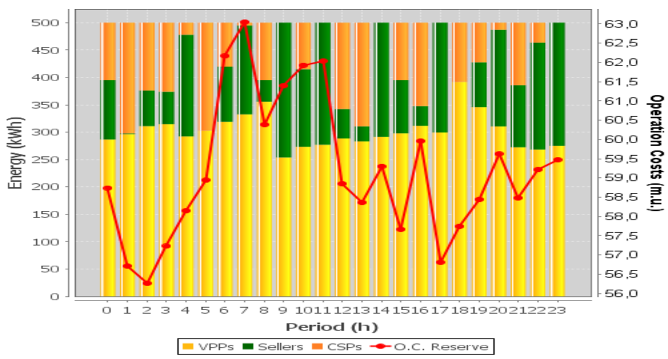

Figure 4. Operation costs and dispatched energy related to the reserve product, for the 24 periods of the day.

The visual aspect of the illustrations presented in all the figures in this case study corresponds to the visualization of the results provided by MASCEM simulator.

VI. Conclusions

Electricity markets with deep economic efficiency concerns must accommodate all the available resources and involved players in a competitive environment. Some of the emerging resources, many of them of small size, require specific considerations when being accommodated in the electricity market. This requires the resource aggregation, which can be done by VPPs that are able to make small resources profitable. Those emerging resources include distributed generation and demand response resources which are of difficulty predictability. So, they require an adequate integration in the electricity market. Resources of higher size can participate directly in the market. The present paper presents the integration of the joint dispatch of energy and reserve in MASCEM simulator. The resources dispatch minimizes the total operation costs resulting from the use of those resources based on the bids submitted by both generation and demand resources, for both energy and reserve products in the market. The integration of the proposed dispatch methodology in MASCEM results in an important tool to be used by buyers, sellers, VPPs, and market operators in order to improve their performance in the context of the electricity market.

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