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A joint approach for strategic bidding of a microgrid in energy and spinning reserve markets

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Abstract

In the electricity market, short-term operation is organized in day-ahead and real-time stages. The two stages that are performed in different time intervals have reciprocal effects on each other. The paper shows the strategy of a microgrid that participates to both day-ahead energy and spinning reserve market. It is supposed that microgrid is managed by a prosumer, a decision maker who manages distributed energy sources, storage units, Information and Communication Technologies (ICT) elements, and loads involved in the grid. The strategy is formulated considering that all decisions about the amount of power to sell in both markets and the price links to the offer, must be taken contextually and at the same time, that is through a joint approach. In order to develop an optimal bidding strategy for energy markets, prosumer implements a non-linear mixed integer optimization model: in this way, by aggregating and coordinating various distributed energy sources, including renewable energy sources, micro-turbines–electricity power plants, combined heat and power plants, heat production plants (boilers), and energy storage systems, prosumer is able to optimally allocate the capacities for energy and spinning reserve market and maximize its revenues from different markets. Moreover, it is considered that both generators and loads can take part in the reserve market. The demand participation happens through both shiftable and curtailable loads. Case studies based on microgrid with various distributed energy sources demonstrate the market behavior of the prosumer using the proposed bidding model.

Keywords

Ancillary service, microgrid, optimal bidding strategy, joint approach, optimization problem

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Introduction

Recently power systems have been undergoing changes to satisfy an increasing energy demand. The microgrids (MGs) concept is one of the proposed solutions to cope with these new challenges. It is based on a cluster of time-varying loads and distributed energy sources, a portion of which includes renewable energy sources (RESs). MGs operate as single controllable system that provides power, and optionally heat, allowing bidirectional power to and from the main medium voltage (MV) power grid.[1–5]

From the system point of view, MGs show the advantages of low investment costs, low pollutant emission, and high operational flexibility. In addition, the MGs are located at the demand side, efficiently offering capacities to meet the local requirements.[6]

Several investigators have analyzed the role played by MGs into the deregulated electricity market, their contribution to energy price reduction and to the reliability system increase, as well as their impact on the best strategy devising to minimize operating costs.

The negotiation process between buyers and sellers in a deregulated electricity market is articulated in different steps: the first is represented by the wholesale energy market and the last by the ancillary services market, in which imbalances between programmed and real flows are deleted.

Although in literature it is possible to find similar decision support models, participation to both energy markets following a joint approach is an important open research issue.

The objective of this paper is to show how the MG develops an optimal coordinated bidding strategy for the day-ahead energy and spinning reserve markets taking into account the "perceived probability." The perceived probability is related to the density of probability that reserve is called for. The equilibrium point between the demand and supply determines the market clearing price (MCP) for each hour MG offers, for the hours in which the electricity price is high, the power resulting from the difference between own load and internal production; when the electricity price is low, MG prefers to buy electricity from the main grid in order to satisfy own load. In both cases the focus is the formulation of an appropriate mathematical optimization model, described in the following.

The model is written in a general and complete manner. It, in fact, considers an MG in which both thermal and electrical loads must be satisfied, so that in the MG only electricity power plants, combined heat and power (CHP) plants, and heat production plants (boilers) are already installed. The presence of thermal and electrical storage systems is also accounted for. Moreover, it is considered that both generators and loads can participate in the reserve market. The demand participation happens through both shiftable and curtailable loads.[7]

Note that a low-voltage MG is characterized by a small amount of total capacity, while the market rules generally require that almost a fixed amount of energy must be offered in the reserve market.[8] In order to respect the power limit, we assume that the bid to present into the market is a virtual aggregated bid, resulting from the offers of more MGs, formulated by each MG in independent way. For this purpose, we hypothesized that prosumer acts as an aggregator on behalf of all.

The remaining of the paper is organized as follows: bidding strategy is discussed in the next section and formulated in "The model" section; case study in the subsequent section; discussion and conclusion are presented in the final section.

The bidding strategy and literature review

From the MG's point of view, the energy and the spinning reserve markets are interrelated and dependent on each other: in fact, as more power is produced for the energy market, as less it can be produced for the reserve market, and vice versa. It implies to "withhold" capacity to offer into the energy market and to offer it into reserve market, or "release" capacity in the energy market and give up to offer it into reserve market.

When MG is a producer for the energy market, providing spinning reserve service means that the value of resultant power delivered to the main grid will be increased; when MG is a consumer in energy market, the value of resultant power absorbed from the main grid will be decreased. In all the cases, the MG produces more and/or consumes less energy.

Two different dispatching strategies are usually used among markets: sequential and joint dispatch.

In the sequential approach, prosumer takes part in the reserve market only after the outcomes of the ahead-day market are known offering, eventually, only the residual produced capacity. However, sequential optimization is more appropriate for simple quantity–price auctions for both energy and reserve for both energy and reserves but with less efficient dispatches. In fact, this strategy does not optimize the MG operation obtaining, almost, a suboptimum solution.[9]

In the joint approach, the decisions about how much power is to be allocated in each market and at what price must be taken a priori and contextually. From an economic point of view, the joint approach provides more efficient dispatches if compared with a sequential approach, and it is usually proposed to solve auctions where bidders must declare their units' technical constraints.[9] So, a joint model must explicitly consider, among decision variables, the powers—those exchanged with the main grid and those generated by each unit, and the curtailable loads, for both markets. These decision variables are added to the shiftable loads and to the levels and powers of the storages.

It said the joint approach provides more efficient dispatches if compared with a sequential approach, and it is usually proposed to solve auctions where bidders must declare their units' technical constraints.[9]

The participation of the reserve market involves that the benefits for MG can increase.

The amount of the additional revenues depends on the way in which reserve payments are made.

More specifically, there are markets in which the reserve power is paid at reserve price, only when reserve is actually used. In others, the reserve power is paid, at reserve price, when reserve is allocated but not used, and, at energy price, when the reserve is used.[10–12]

The problem considered in this paper was dealt with in literature almost from the point of view of traditional generation companies[13] or the virtual power plant (VPP),[14,15] using sequential models[16–21] or joint model.[6,22–32]

In Ferruzzi et al.[33] an arbitrage strategy for VPPs by participating in energy, spinning reserve, and reactive power markets is presented. In Rossi,[4] a risk-averse optimal offering model for a VPP is proposed in the joint energy and reserve markets.

However, papers that address the problem with reference or MGs exist in the literature[6,34,35] although in most of the studies, only the first stage of energy management has been considered.[13–15,36–38] This probably happens because MG is characterized by a small amount of total capacity, while the market rules generally require that almost a fixed amount of energy must be offered in the reserve market.

In this work, indeed, the main differences can be summarized as follows: participation of an MG grid connected mode in both the energy markets by a prosumer. It takes part in the markets both as producer and consumer according to energy price values, internal load and grid constraints. The participation also in the reserve market introduces an additional level of complexity in the MG operation but offers the potential for additional revenue. In order to respect the MG power limits, authors assume that the bid to present into the market is an aggregated bid, resulting from the offers of more MGs.[39] For this purpose, we hypothesized that prosumer acts as an aggregator on behalf of all. The study is developed with reference to the Italian framework. Moreover, an optimization model to minimize the operation costs of an MG in the presence of uncertainties is shown: different from the others presented in literature, it takes into account not only the uncertainties from RESs, but also the uncertainties linked to the different energy prices. Authors underline that none of the last citied works formulate a model that allows to deal with together the cases of the call and of the not call the reserve: this is particularly relevant when intertemporal constraints exist (i.e. as those introduced by shiftable loads and storage systems).

In particular, authors assume that a "perceived probability", r_t, that reserve is called, is equal to 0 (MG does not take part in reserve market) or to 1 (the MG takes part in the reserve market).

The perceived probability is related to the density of probability that the reserve is called, obtained by analyzing historical series, different from hour to hour.

Furthermore, none of the citied works considers the cogeneration and none treats shiftable loads.

The model

A novel model of day energy and reserve management of MG is proposed. It formulates a nonlinear mixed integer programming model to evaluate how MG develops an optimal bidding strategy in energy markets. The optimal management problem consists in researching, hour by hour during the day, the values of energy exchanged with the main distribution network, the energy production of each dispatchable unit, the energy charged to/discharged from the storage units, and the controllable load profiles that optimize an economic objective. Also the choices of the thermoelectric units that must be in operation on an hourly base and the determination of the internal network status consistent with operating constraints are part of the problem.

The optimization is extended simultaneously to all 24 h of the management period because the presence of storage systems and shifting actions introduce intertemporal constraints.

It is assumed that all different production units (generators and cogenerators as well as the curtailable loads) have the requirements to provide reserve service; the load shedding is used also for the energy market; the MG can estimate fixed loads, RES production, and prices of energy and spinning reserve markets for each hour through the analysis of time series; the MG knows the density of probability that the reserve will be called to produce, which, according to Yamin,[28] and contrary to Bai et al.,[16] Chitkara et al.,1[7] and Jia et al.[18] has different values from hour to hour.

Objective function

The revenues, R, are related to energy sold in the reserve market and, if there is, in the energy market. Neglecting the management costs of storage and shifting, the costs, C, are related, instead, to the energy bought from the main grid, if there is, to production costs of generators, cogenerators, and boilers and, finally, to load shedding.

That said, assuming that the exchanged power in the energy market is positive if it is bought and negative if it is sold, and assuming that the energy market price is equal in the buying and selling phases, the objective function to maximize is

$$
\begin{aligned}
E(R-C) = {} & \sum_{t=1}^{24} r_t \rho_t^r P_{gridt}^r + \sum_{t=1}^{24} \rho_t^e P_{gridt}^e - \sum_{t=1}^{24} (1-r_t) \Bigg[\sum_{j\in\Omega_C} Cc_j\left(P_{Ce_{t,j}}^e\right) \\
& + \sum_{j\in\Omega_B} C_{B_j}\left(P_{B_{t,j}}\right) + \sum_{j\in\Omega_{G_j}} C_{G_j}\left(P_{G_{t,j}}^e\right) + \sum_{j\in\Omega_{DCU}} C_{D_{CUj}}\left(P_{DCU_{t,j}}^e\right) \Bigg] \\
& - \sum_{t=1}^{24} (r_t) \Bigg[\sum_{j\in\Omega_C} Cc_j\left(P_{Ce_{t,j}}^e + P_{Ce_{t,j}}^r\right) + \sum_{j\in\Omega_B} C_{B_j}\left(P_{B_{t,j}}\right) \\
& + \sum_{j\in\Omega_G} C_{G_j}\left(P_{G_{t,j}}^e + P_{G_{t,j}}^r\right) + \sum_{j\in\Omega_{DCU}} C_{D_{CUj}}\left(P_{DCU_{t,j}}^e + P_{DCU_{t,j}}^r\right) \Bigg]
\end{aligned}
\tag{1}
$$

The first summation of equation (1) represents the revenue, R_r derived from the participation to the reserve market, supposing that the reserve power is paid, at reserve price only when reserve is actually used.

If, moreover, the reserve power is paid, at reserve price, when reserve is allocated but not used, and, at energy price, when the reserve is used, it must be changed in

$$
E(R^r) = \sum_{t=1}^{24} [(1-r_t)\rho^r + r_t \rho^e] P_{grid_t}^r
$$

Constraints

The basic equality constraints are the thermal and electric balance constraints.

Assuming that the storage powers are positive during the discharge and negative during the charge, they are[a]

$$
\begin{aligned}
& (1-r_t)\left(\sum_{j\in\Omega_C} \frac{P_{Ce_{t,j}}^e}{\eta_j} + \sum\nolimits_{j\in\Omega_B} P_{B_{t,j}} \right) + r_t \left(\sum_{j\in\Omega_C} \frac{P_{Ce_{t,j}}^e}{\eta_j} + \sum_{j\in\Omega_C} \frac{P_{Ce_{t,j}}^r}{\eta_j} + \sum_{j\in\Omega_B} P_{B_{t,j}} \right) \\
& \quad = \sum_{j\in\Omega_{Dth}} P_{Dsh_{t,j}} + \sum_{j\in\Omega_{ST}} P_{ST_{t,j}} \quad t = (1 \ldots .24)
\end{aligned}
\tag{2}
$$

$$\sum_{t=1}^{24}(1-r_t)\Bigg(\sum\sum_{j\in\Omega_c}\left(P^e_{G_{t,j}}+P^r_{Ce_{t,j}}\right)+P^e_{gridt}-\sum_{j\in\Omega_{DF}}P_{DF_{t,j}}$$
$$+\sum_{j\in\Omega_{DC}}P^e_{DCU_{t,j}}-\sum_{j\in\Omega_{DSH}}P_{DSH_{t,j}}-\sum_{j\in\Omega_{SE}}P_{SE_{t,j}}\Bigg)$$
$$+\sum_{t=1}^{24}r\Bigg(\sum_{t=1}^{24}P^e_{Ce_{t,j}}+P^r_{Ce_{t,j}}+\sum_{j\in\Omega_G}P^e_{G_{t,j}}+\sum_{j\in\Omega_G}P^r_{G_{t,j}}+P^e_{gridt} \tag{3}$$
$$+P^e_{gridt}-\sum_{j\in\Omega_{DF}}P_{DF_{t,j}}+\sum_{j\in\Omega_{DC}}P^e_{DCU_{t,j}}+\sum_{j\in\Omega_{DC}}P^r_{DCU_{t,j}}$$
$$-\sum_{j\in\Omega_{DSH}}P_{DSH_{t,j}}-\sum_{j\in\Omega_{SE}}P_{SE_{t,j}}\Bigg)\quad t=(1\ldots.24)$$

In equation (3) $P_{DSHt,j}$ is the shifted power of the jth shiftable load.

The relationship between the loads before and after shifting can be represented by introducing binary variables $u_{t,j}$.

The condition $u_{t,j}=1$ identifies the initial interval t where the jth shiftable load starts to be supplied for the next S_j hours. Considering that the profile of the jth shiftable load starts only once, only a binary variable can be equal to one. Moreover, only the first (T_j-S_j+1) binary variables can be defined because each $u_{t,j}$ variable is associated with the next (S_j+1) variables $P_{DSHt,j}$

It must happen that

$$\sum_{t=1}^{T_{j-}S_j+1}u_{t,j}=1(j\in D_{SH}) \tag{4}$$

Then, let us consider that only the variables associated with $u_{t,j}=1$, i.e. $P_{DSH_{t,j}},P_{DSH_{t+1,j}};,\ldots,P_{DSH_{t+k,j}}$, take positive values. Specifically, each $P_{DSH_{t,j}}$j with $k=t-s+1$, takes the value $DSH_{t,j}$. This way, the links between shiftable and shifted loads are

$$P_{D_{SH\,t,j}}=\sum_{s=1}^{t}D_{SH(t-k+1)}*u_{k,j}\quad(j\in D_{SH};t=1,\ldots,T_j-S_j+1) \tag{5}$$

Mathematically the problem is a nonlinear mixed integer programming problem. However, if the shiftable loads are not taken into account, it becomes an easier nonlinear programming problem.

When there are storage units, the objective function is the same because the operation costs of storage can be neglected.

Additional equality constraints can be derived from modeling the storage units. In fact, it is necessary to express the variation of the storage levels and the restoration of the initial levels as: the variation of the storage levels

$$W_{SE_{t,j}} = W_{SE_{t-1,j}} + P_{SE_{t,j}} \quad (j \in \Omega_{SE};\ t = 1, \ldots, 24) \tag{6a}$$

$$W_{ST_{t,j}} = W_{ST_{t-1,j}} + k_{s_j} P_{ST_{t,j}} \quad (j \in \Omega_{SE};\ t = 1, \ldots, 24) \tag{6b}$$

Finally, inequality constraints express the limits on internal production and maximum amount of exchangeable power, bought or sold, in the main grid must be considered:

- limits on cogenerators production

$$0 \le P^r_{Ce_j} \le \left(P^{Max}_{Ce_j} - P^e_{Ce_j}\right) \quad (j \in \Omega_C;\ t = 1, \ldots, 24) \tag{7a}$$

$$P^e_{Ce_j} + P^r_{Ce_j} \le P^{Max}_{Ce_j} \quad (j \in \Omega_C;\ t = 1, \ldots, 24) \tag{7b}$$

- limits on boilers production

$$P^m_{B_j} \le P_{B_{t,j}} \le P^M_{B_j} \quad (j \in \Omega_C;\ t = 1, \ldots, 24) \tag{8}$$

- limits on generators production

$$0 \le P^r_{G_{t,j}} \le \left(P^{Max}_{G_j} - P^e_{G_j}\right) \quad (j \in \Omega_G;\ t = 1, \ldots, 24) \tag{9a}$$

$$P^e_{G_{t,j}} + P^r_{G_{t,j}} \le P^{Max}_{G_j} \quad (j \in \Omega_G;\ t = 1, \ldots, 24) \tag{9b}$$

- limits if exchangeable power in the main grid

$$-P^{Max}_{grid_t} \le P_{grid_t} \le P^{Max}_{grid_t} \quad (t = 1, \ldots, 24) \tag{10}$$

It is noted that the model does not evaluate the arbitrage opportunities: MG cannot buy more energy in the energy market to sell more into the reserve market. If arbitrage is admitted, constraints (7) and (9) must be written as

$$0 \le P^r_{Ce_j} \le \left(P^{Max}_{Ce_j} - P^e_{Ce_j}\right) (j \in \Omega_C;\ t = 1, \ldots, 24) \tag{11a}$$

$$0 \le P^r_{G_{t,j}} \le \left(P^{Max}_{G_j} - P^{min}_{G_j}\right) \quad (j \in \Omega_G;\ t = 1, \ldots, 24) \tag{11b}$$

Case study

The model described in Siano et al.[1] is applied to a residential MG, grid connected, composed of different entities, i.e. hotel, sports center, markets, offices, and buildings. Thermal and electric total loads, with reference to a summer day, are reported in Table 1. The loads are reduced by the renewable energy.

Some loads can be shifted, so it is possible moving them from peak load to valley load. Washing machines, dryers, dishwasher, air conditioners, irons, and electric coffee makers are shiftable loads. The total number of devices taken into account for the analysis is 1260 and their characteristics are reported in Table 2.

In MG there are six power generators: two power plants producing only electricity (G_1, G_2) and four producing electricity and heat (Ce_1, Ce_2, Ce_3, Ce_4). To satisfy thermal loads, there is also a boiler.

The generator and cogenerators cost functions are assumed quadratic, while the boiler cost function is assumed to be linear as follows

$$C_{C_j}(P_{Ce_{t,j}}) = \alpha_{Cj} P^2_{Ce_{t,j}} + \beta_{Cj} P_{Ce_{t,j}} + \gamma_{C_j}$$

$$C_{G_j}(P_{Ce_{t,j}}) = \alpha_{Gj} P^2_{Ce_{t,j}} + \beta_{Gj} P_{Ce_{t,j}} + \gamma_{G_j}$$

Table 1. Hourly electrical and thermal loads.

Hours [h]	P_{De_t} [kWe]	P_{Dth} [kWe]
1	440.0	320.0
2	440.0	295.0
3	440.0	275.0
4	440.0	275.0
5	440.0	495.0
6	740.0	605.0
7	1200.0	1305.0
8	1905.0	3560.0
9	2345.0	3570.0
10	2405.0	3690.0
11	2420.0	3625.0
12	2440.0	4095.0
13	2470.0	4125.0
14	2465.0	4300.0
15	2450.0	4255.0
16	2395.0	3950.0
17	2360.0	3905.0
18	2335.0	3605.0
19	1695.0	1695.0
20	1425.0	1680.0
21	1295.0	1425.0
22	955.0	1020.0
23	530.0	520.0
24	425.0	390.0

$$C_{B_j}(P_{B_{t,j}}) = \beta_{Cj} P_{B_j} + \gamma_{B_j}$$

Technical and economic characteristics of the generators and cogenerators are reported in Table 2; in particular are reported the minimum and maximum power of each unit and the coefficients α_{Cj}, β_{Cj}, γ_{Cj}, α_{Gj}, β_{Gj}, and γ_{Cj}. Instead, the maximum power of boiler is 4500 kW and the coefficient β_j is equal to 55.0.

In Table 3, energy and spinning reserve market prices are reported. They are available on line on the Gestore dei Mercati Energetici website (www.mercatoelettrico.org).

Table 2. Technical and economic characteristics of the generation power plants.

Units	$P^m_{G_j}$ [kW]	$P^M_{G_j}$ [kW]	γ_{G_j} [€]	β_{G_j} [€/MW_h]	α_{G_j} [€/$MW_h{}^2$]	$P^m_{ce_j}$ [kW]	$P^m_{ce_j}$ [kW]	γ_{Ce_j} [€]	β_{Ce_j} [€/MW_h]	α_{Ce_j} [€/$MW_h{}^2$]
G_1	36.0	180.0	892.0	25.8	0.021					
G_2	36.0	180.0	892.0	33.4	0.042					
Ce_1						80.0	400.0	1017.0	10.4	0.0005
Ce_2						80.0	400.0	1017.0	22.7	0.0005
Ce_3						10.0	80.0	484.0	48.1	0.105
Ce_4						10.0	80.0	840.0	54.2	0.233

Table 3. Energy and spinning reserve market prices.

Hours [h]	ρ^e_t [€]	ρ^r_t [€]
1	41.7	48.0
2	39.7	45.7
3	38.0	43.8
4	36.0	41.4
5	36.0	41.5
6	36.0	41.4
7	39.8	45.8
8	44.6	51.3
9	49.5	56.9
10	51.8	59.6
11	46.3	53.3
12	40.8	47.0
13	39.3	45.2
14	38.5	44.2
15	43.7	50.2
16	42.0	48.3
17	44.9	51.6
18	48.3	55.5
19	44.5	51.1
20	45.0	51.8
21	55.0	63.3
22	59.4	68.3
23	55.0	63.3
24	50.7	58.3

The model, described in Siano et al.,[1] was implemented for different configurations. It is supposed, first of all, that all loads are fixed and that all units (cogenerators and generators) produce only electricity, so that only the boiler satisfies the thermal load. In this configuration, two cases are analyzed that correspond to a perceived probability r_t, that the reserve is not called to produce or, instead, is called to produce: $r_t = r = 0$ (case 1) and $r_t = r = 1$ (case 2).

It is then considered the cogeneration always assuming the presence only of fixed loads. Also in this configuration are considered the cases $r_t = r = 0$ (case 3) and $r_t = r = 1$ (case 4).

The cases 5, 6, and 7 consider always the cogeneration, but a percentage of the loads is supposed to be shiftable. Now, in addition to cases $r_t = r = 0$ (case 5) and $r_t = r = 1$ (case 6), it is also considered the case in which the probability is not constant, assuming the value 0 or 1 depending on the interval (case 7).

It is finally also examined the configuration in which is present a storage system for $r = 0$ (case 8) and $r = 1$ (case 9). For the eight cases considered, the model was implemented in the version that does not provide the possibility of arbitrage, i.e. the possibility that MG buys in the electricity energy market only in order to sell it in the reserve market. In the following, however, some examples will be provided to show what would be the benefit if the arbitrage was permitted.

Yet, for all the cases analyzed, the revenue from the participation in reserve market is calculated taking into account that reserve is paid, at reserve price, only when reserve is actually used.

Not_cogeneration

In Table 4 are reported results for r_t=0.

- the powers produced and power exchanged with main grid are internal to the domain,
- the units produce until their marginal costs (that vary in the ranges reported in Table 5) reach the electricity market price (see G_2, for example, in hours 1, 2, 3, 7, 8).

If units with marginal cost are higher of electricity market price produced, it means that the constraint related to the maximum energy exchanged with the main grid (assumed equal to 1200 kW) is reached: MG cannot withdraw more from the main grid and the units produced, according to the criterion of increasing marginal costs, until the balance constraint is satisfied (this happens, for example, at the units Ce3 and Ce_4 in hours 12–15).

It is important to note that MG is producer in the hours 1–6 and 22–24, while it is consumer in the hours 7–21, according to how internal production is related to internal consumption.

Different are the operating results for $r = 1$, as shown in Table 6 which now lists also the quantity relating to the reserve market.

MG tends to take part also in the reserve market, being the reserve market price always higher than electricity market price (MCP).

In the intervals in which the power exchanged Pegridt is not bound to the maximum value, all the units offer the minimum power into the energy market.

Those that have the marginal cost are always lower than the reserve price (G_1, G_2, Ce_1, and Ce_2) sell to the reserve market the residual capacity; the units that, indeed, have marginal cost always greater than reserve price (Ce_3 and Ce_4) do not offer in the reserve market.

Table 4. Not cogeneration with r = 0. Case 1.

Hours [h]	ρ^e[€]	$P_{De_t}[kW_e]$	$P^e_{G_{t,1}}[kW_e]$	$P^e_{G_{t,2}}[kW_e]$	$P^e_{ce_{t,1}}[kW_e]$	$P^e_{ce_{t,2}}[kW_e]$	$P^e_{ce_{t,3}}[kW_e]$	$P^e_{ce_{t,4}}[kW_e]$	$P^e_{grid_t}[kW_e]$
1	41.7	440.0	180.0	87.1	400.0	400.0	10.0	10.0	−647.1
2	39.7	440.0	180.0	63.3	400.0	400.0	10.0	10.0	−623.3
3	38.0	440.0	180.0	43.6	400.0	400.0	10.0	10.0	−603.6
4	36.0	440.0	180.0	36.0	400.0	400.0	10.0	10.0	−596.0
5	36.0	440.0	180.0	36.0	400.0	400.0	10.0	10.0	−596.0
6	36.0	740.0	180.0	36.0	400.0	400.0	10.0	10.0	−296.0
7	39.8	1200.0	180.0	64.4	400.0	400.0	10.0	10.0	135.6
8	44.6	1905.0	180.0	121.1	400.0	400.0	10.0	10.0	783.9
9	49.5	2345.0	180.0	180.0	400.0	400.0	10.0	10.0	1165.0
10	51.8	2405.0	180.0	180.0	400.0	400.0	35.0	10.0	1200.0
11	46.3	2420.0	180.0	180.0	400.0	400.0	50.0	10.0	1200.0
12	40.8	2440.0	180.0	180.0	400.0	400.0	60.0	20.0	1200.0
13	39.3	2470.0	180.0	180.0	400.0	400.0	60.0	50.0	1200.0
14	38.5	2465.0	180.0	180.0	400.0	400.0	60.0	45.0	1200.0
15	43.7	2450.0	180.0	180.0	400.0	400.0	60.0	30.0	1200.0
16	42.0	2395.0	180.0	160.0	400.0	400.0	25.0	10.0	1200.0
17	44.9	2360.0	180.0	164.9	400.0	400.0	10.0	10.0	1200.0
18	48.3	2335.0	180.0	119.6	400.0	400.0	10.0	10.0	1170.1
19	44.5	1695.0	180.0	126.2	400.0	400.0	10.0	10.0	575.4
20	45.0	1425.0	180.0	180.0	400.0	400.0	10.0	10.0	298.8
21	55.0	1295.0	180.0	180.0	400.0	400.0	32.9	10.0	92.1
22	59.4	955.0	180.0	180.0	400.0	400.0	53.8	11.2	−270.0
23	55.0	530.0	180.0	180.0	400.0	400.0	32.9	10.0	−672.9
24	50.7	425.0	180.0	180.0	400.0	400.0	12.5	10.0	−757.5

Table 5. Marginal costs in correspondence of minimum and maximum power produced.

Units	λ_j^m	λ_j^M
G_1	27.3	33.3
G_2	37.4	49.5
G_{e1}	10.4	10.8
G_{e2}	23.1	24.8
G_{e3}	50.2	60.7
G_{e4}	58.9	82.1

As said before, this is true until the power exchanged with the main grid is not at maximum. When it happens, (see 8–19 h) the units, even those with marginal cost higher than market price, are obliged to produce in the electricity market in order to respect the balance constraint and produce respecting the criterion of increasing marginal costs. It is noted that in the intervals 1–6 and 22–24, contrary to the case 1, MG prefers to buy in the electricity market in order to have the opportunity to sell more in the reserve market.

The just commented results are completely different from those that would obtain by following the sequential approach rather than the proposed joint approach.

Table 6. Not cogeneration with r = 1.

Hours [h]	ρ_t^e [€]	P_{De_t} [kW$_e$]	$P^e_{G_{t,1}}$ [kW$_e$]	$P^e_{G_{t,2}}$ [kW$_e$]	$P^e_{ce_{t,1}}$ [kW$_e$]	$P^e_{ce_{t,2}}$ [kW$_e$]	$P^e_{ce_{t,3}}$ [kW$_e$]	$P^e_{ce_{t,4}}$ [kW$_e$]	$P^e_{grid_t}$ [kW$_e$]	P^r_t €	$P^r_{G_{t,1}}$ [kW$_e$]	$P^r_{G_{t,2}}$ [kW$_e$]	$P^r_{Ce_{t,1}}$ [kW$_e$]	$P^r_{Ce_{t,2}}$ [kW$_e$]	$P^r_{Ce_{t,3}}$ [kW$_e$]	$P^r_{Ce_{t,4}}$ [kW$_e$]	$P^r_{grid_t}$ [kW$_e$]
1	41.7	440	36.0	36.0	80.0	80.0	35.0	10.0	188.0	48.0	144.0	144.0	320.0	320.0	0.0	0.0	−928.0
2	39.7	440	36.0	36.0	80.0	80.0	10.0	10.0	188.0	45.7	144.0	144.0	320.0	320.0	0.0	0.0	−928.0
3	38	440	36.0	36.0	80.0	80.0	10.0	10.0	188.0	43.8	144.0	111.5	320.0	320.0	0.0	0.0	−895.5
4	36	440	36.0	36.0	80.0	80.0	10.0	10.0	188.0	41.4	144.0	83.0	320.0	320.0	0.0	0.0	−867.0
5	36	440	36.0	36.0	80.0	80.0	10.0	10.0	188.0	41.5	144.0	84.6	320.0	320.0	0.0	0.0	−868.6
6	36	740	36.0	36.0	80.0	80.0	10.0	10.0	488.0	41.4	144.0	83.0	320.0	320.0	0.0	0.0	−867.3
7	39.8	1200	36.0	36.0	80.0	80.0	10.0	10.0	948.0	45.8	144.0	144.0	320.0	320.0	0.0	0.0	−928.0
8	44.6	1905	36.0	145.0	400.0	213.0	10.0	10.0	1200.0	51.3	144.0	144.0	0.0	187.0	15.0	0.0	−490.0
9	49.5	2345	180.0	180.0	400.0	400.0	10.0	10.0	1200.0	56.9	0.0	35.0	0.0	0.0	42.0	5.9	−82.9
10	51.8	2405	180.0	180.0	400.0	400.0	35.0	10.0	1200.0	59.6	0.0	0.0	0.0	0.0	25.6	11.6	−36.6
11	46.3	2420	180.0	180.0	400.0	400.0	50.0	10.0	1200.0	53.3	0.0	0.0	0.0	0.0	10.0	0.0	−10.0
12	40.8	2440	180.0	180.0	400.0	400.0	60.0	20.0	1200.0	47.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
13	39.3	2470	180.0	180.0	400.0	400.0	60.0	50.0	1200.0	45.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0
14	38.5	2465	180.0	180.0	400.0	400.0	60.0	45.0	1200.0	44.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0
15	43.7	2450	180.0	180.0	400.0	400.0	60.0	30.0	1200.0	50.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0
16	42	2395	180.0	180.0	400.0	400.0	25.0	10.0	1200.0	48.3	0.0	0.0	0.0	0.0	1.0	0.0	−1.0
17	44.9	2360	180.0	160.0	400.0	400.0	10.0	10.0	1200.0	51.6	0.0	20.0	0.0	0.0	16.6	0.0	−36.6
18	48.3	2335	180.0	135.0	400.0	400.0	10.0	10.0	1200.0	55.5	0.0	45.0	0.0	0.0	35.2	2.8	−83.0
19	44.5	1695	36.0	36.0	323.0	80.0	10.0	10.0	1200.0	51.1	144.0	144.0	77.0	320.0	14.4	0.0	−699.4
20	45	1425	36.0	36.0	80.0	80.0	10.0	10.0	1173.0	51.8	144.0	144.0	320.0	320.0	17.4	0.0	−945.4
21	55	1295	36.0	36.0	80.0	80.0	10.0	10.0	1043.0	63.3	144.0	144.0	320.0	320.0	19.4	0.0	−997.4
22	59.4	955	36.0	36.0	80.0	80.0	10.0	10.0	703.0	68.3	144.0	144.0	320.0	320.0	50.0	31.5	−1009.5
23	55	530	36.0	36.0	80.0	80.0	10.0	10.0	278.0	63.3	144.0	144.0	320.0	320.0	50.0	19.4	−997.4
24	50.7	425	36.0	36.0	80.0	80.0	10.0	10.0	173.0	58.3	144.0	144.0	320.0	320.0	50.0	9.0	−987.0

Cogeneration

Typical cogeneration plants (CHP) are driven by the thermal demand and the systems are dimensioned for thermal base load: that means they operate continuously for many hours of the year. In this work in which CHPs take part to the energy market, several possibilities can be realized, related to the variable energy price. Consequently, the output power of CHP units could be between the technical minimum and maximum rates.

In Table 7 are reported the operating results for $r = 0$.

In this case, for the cogenerators, the criterion of increasing marginal costs requires that the cogenerators work until their marginal costs reach the value given by the sum of the electricity market price and the ratio between the marginal cost of boiler and the efficiency of cogeneration (the latter assumed equal to 0.8 for all the cogenerators). But this value is never achieved in our case due to high marginal cost of boiler. In comparison to the case 1, in the intervals 1–6 and 23–24, since the thermal load is low, the cogenerators with lower marginal costs reduce the production and the cogenerators with higher marginal costs continue to work at minimum. Differently, the generators work at maximum. In the other intervals, characterized by higher thermal loads, all units produce at maximum, resulting in that the maximum value of the power exchanged with main grid is never reached. As in the case 1, MG sells in the intervals.

The total power produced by each unit remains the same as the case 3, but it is distributed in the two markets taking into account the balance constraints and the prices. In the intervals in which Pe_{gridt} does not reach the maximum, all the units offer the minimum power into the electricity market and offer as much as possible in the reserve market. Note that, for example, as G_2 does not sell, as in the case 2, the residual capacity: the thermal load is low and, to satisfy it, it is sufficient that produce Ce_5 and Ce_6, that in the energy market are constrained to produce the minimum and G_1, which has a lower marginal cost than G_2. As in the case 2, when the power exchanged with main grid reaches their maximum (see 8–19 h), the units, even those with marginal cost higher than market price, are obliged to produce in the energy market if that is necessary to respect the balance constraint. As in the case 2 and contrary to the case 3, in the intervals 1–6 and 22–24, MG prefers to buy in the energy market in order to have the opportunity to sell more in the reserve market. The just commented results are completely different from those that would be obtained by following the sequential approach rather than the proposed joint approach.

Tables 8 and 9 show electrical and thermal quantities, respectively, in case of cogeneration and $r = 1$.

Shiftable loads

Table 10 shows the characteristics of the shiftable loads considered. More precisely, it shows the type of loads, the cycle duration of each load, the shiftable power of each load in the hourly intervals.

Each load is composed by a number N_j of devices, each of power d_{SHs} (Table 11). In Tables 12 and 13 are reported the results for $r = 0$; in Tables 14 and 15 those for $r = 1$. In particular, the first Tables 12 and 13 show the position preshift and postshift of the loads; the second Table 14 the complete state of the MG postshift.

As we can easily see, the analysis of the tables shows that each load is shifted, if own T_j allows, in the time intervals equal in number to the hours of S_j—to which corresponds the

Table 7. Cogeneration with r = 0.

Hour [h]	ρ^e_t [€]	P_{De_t} [kW$_e$]	$P^e_{G_{t,1}}$ [kW$_e$]	$P^e_{G_{t,2}}$ [kW$_e$]	$P^e_{ce_{t,1}}$ [kW$_e$]	$P^e_{ce_{t,2}}$ [kW$_e$]	$P^e_{ce_{t,3}}$ [kW$_e$]	$P^e_{ce_{t,4}}$ [kW$_e$]	$P^e_{grid_t}$ [kW$_e$]	$P_{D_{th}}$ [kW$_e$]	$P_{G_{th_{t,1}}}$ [kW$_e$]	$P_{Gth_{t,2}}$ [kW$_e$]	$P_{Cth_{t,1}}$ [kW$_{th}$]	$P_{Cth_{t,2}}$ [kW$_{th}$]	$P_{Cth_{t,3}}$ [kW$_{th}$]	$P_{Cth_{t,4}}$ [kW$_{th}$]	P_{B_t} [kW$_{th}$]
1	41.7	440	180.0	180.0	212.0	80.0	10.0	10.0	−232.0	320.0	0	0	265.0	100.0	12.5	12.5	0.0
2	39.7	440	180.0	180.0	156.0	80.0	10.0	10.0	−176.0	295.0	0	0	195.0	100.0	12.5	12.5	0.0
3	38	440	180.0	180.0	136.0	80.0	10.0	10.0	−156.0	275.0	0	0	170.0	100.0	12.5	12.5	0.0
4	36	440	180.0	180.0	120.0	80.0	10.0	10.0	−140.0	275.0	0	0	150.0	100.0	12.5	12.5	0.0
5	36	440	180.0	180.0	120.0	80.0	10.0	10.0	−140.0	495.0	0	0	150.0	100.0	12.5	12.5	0.0
6	36	740	180.0	180.0	296.0	80.0	10.0	10.0	−16.0	605.0	0	0	370.0	100.0	12.5	12.5	0.0
7	39.8	1200	180.0	180.0	384.0	80.0	10.0	10.0	356.0	1305.0	0	0	480.0	100.0	12.2	12.5	0.0
8	44.6	1905	180.0	180.0	400.0	400.0	60.0	60.0	625.0	3560.0	0	0	500.0	100.0	75.0	75.0	200.0
9	49.5	2345	180.0	180.0	400.0	400.0	60.0	60.0	1065.0	3570.0	0	0	500.0	500.0	75.0	75.0	2410.0
10	51.8	2405	180.0	180.0	400.0	400.0	60.0	60.0	1125.0	3690.0	0	0	500.0	500.0	75.0	75.0	2540.0
11	46.3	2420	180.0	180.0	400.0	400.0	60.0	60.0	1140.0	3625.0	0	0	500.0	500.0	75.0	75.0	2475.0
12	40.8	2440	180.0	180.0	400.0	400.0	60.0	60.0	1160.0	4095.0	0	0	500.0	500.0	75.0	75.0	2945.0
13	39.3	2470	180.0	180.0	400.0	400.0	60.0	60.0	1190.0	4125.0	0	0	500.0	500.0	75.0	75.0	2975.0
14	38.5	2465	180.0	180.0	400.0	400.0	60.0	60.0	1185.0	4300.0	0	0	500.0	500.0	75.0	75.0	3150.0
15	43.7	2450	180.0	180.0	400.0	400.0	60.0	60.0	1170.0	4255.0	0	0	500.0	500.0	75.0	75.0	3105.0
16	42	2395	180.0	180.0	400.0	400.0	60.0	60.0	115.0	3950.0	0	0	500.0	500.0	75.0	75.0	2800.0
17	44.9	2360	180.0	180.0	400.0	400.0	60.0	60.0	1080.0	3905.0	0	0	500.0	500.0	75.0	75.0	2755.0
18	48.3	2335	180.0	180.0	400.0	400.0	60.0	60.0	1055.0	3605.0	0	0	500.0	500.0	75.0	75.0	1455.0
19	44.5	1695	180.0	180.0	400.0	400.0	60.0	60.0	415.0	1695.0	0	0	500.0	500.0	75.0	75.0	1455.0
20	45	1425	180.0	180.0	400.0	400.0	60.0	60.0	145.0	1680.0	0	0	500.0	500.0	75.0	75.0	545.0
21	55	1295	180.0	180.0	400.0	400.0	60.0	60.0	15.0	1425.0	0	0	500.0	500.0	75.0	75.0	530.0
22	59.4	955	180.0	180.0	400.0	400.0	60.0	60.0	−325.0	1020.0	0	0	500.0	500.0	75.0	75.0	275.0
23	55	530	180.0	180.0	400.0	396.0	10.0	10.0	−646.0	520.0	0	0	500.0	495.0	12.5	12.5	0.0
24	50.7	425	180.0	180.0	316.0	80.0	10.0	10.0	−351.0	390.0	0	0	395.0	100.0	12.5	12.5	0.0

Table 8. Cogeneration with r = 1. Electrical quantities.

Hours [h]	ρ^e_t [€]	P_{De_t} [kW$_e$]	$P^e_{G_{t,1}}$ [kW$_e$]	$P^e_{G_{t,2}}$ [kW$_e$]	$P^e_{ce_{t,1}}$ [kW$_e$]	$P^e_{ce_{t,2}}$ [kW$_e$]	$P^e_{ce_{t,3}}$ [kW$_e$]	$P^e_{ce_{t,4}}$ [kW$_e$]	$P^e_{grid_t}$ [kW$_e$]	P^r_t [kW$_e$]	$P^r_{G_{t,1}}$ [$\in$]	$P^r_{G_{t,2}}$ [kW$_e$]	$P^r_{Ce_{t,1}}$ [kW$_e$]	$P^r_{Ce_{t,2}}$ [kW$_e$]	$P^r_{Ce_{t,3}}$ [kW$_e$]	$P^r_{Ce_{t,4}}$ [kW$_e$]
1	41.7	440.0	36.0	36.0	80.0	80.0	10.0	10.0	188.0	48.0	144.0	144.0	132.0	0.0	0.0	0.0
2	39.7	440.0	36.0	36.0	80.0	80.0	10.0	10.0	188.0	45.7	144.0	144.0	76.0	0.0	0.0	0.0
3	38.0	440.0	36.0	36.0	80.0	80.0	10.0	10.0	188.0	43.8	144.0	111.5	56.0	0.0	0.0	0.0
4	36.0	440.0	36.0	36.0	80.0	80.0	10.0	10.0	188.0	41.4	144.0	83.0	40.0	0.0	0.0	0.0
5	36.0	440.0	36.0	36.0	80.0	80.0	10.0	10.0	188.0	41.5	144.0	84.6	40.0	0.0	0.0	0.0
6	36.0	740.0	36.0	36.0	80.0	80.0	10.0	10.0	488.0	41.4	144.0	83.0	216.0	0.0	0.0	0.0
7	39.8	1200.0	36.0	36.0	80.0	80.0	10.0	10.0	948.0	45.8	144.0	144.0	304.0	0.0	0.0	0.0
8	44.6	1905.0	36.0	145.0	400.0	213.0	10.0	10.0	1200.0	51.3	144.0	144.0	304.0	0.0	0.0	0.0
9	49.5	2345.0	180.0	180.0	400.0	400.0	10.0	10.0	1200.0	56.9	0.0	35.0	0.0	0.0	50.0	50.0
10	51.8	2405.0	180.0	180.0	400.0	400.0	35.0	10.0	1200.0	59.6	0.0	0.0	0.0	0.0	25.0	50.0
11	46.3	2420.0	180.0	180.0	400.0	400.0	50.0	10.0	1200.0	53.3	0.0	0.0	0.0	0.0	10.0	50.0
12	40.8	2440.0	180.0	180.0	400.0	400.0	60.0	20.0	1200.0	47.0	0.0	0.0	0.0	0.0	0.0	40.0
13	39.3	2470.0	180.0	180.0	400.0	400.0	60.0	50.0	1200.0	45.2	0.0	0.0	0.0	0.0	0.0	10.0
14	38.5	2465.0	180.0	180.0	400.0	400.0	60.0	45.0	1200.0	44.2	0.0	0.0	0.0	0.0	0.0	15.0
15	43.7	2450.0	180.0	180.0	400.0	400.0	60.0	30.0	1200.0	50.2	0.0	0.0	0.0	0.0	0.0	30.0
16	42.0	2395.0	180.0	180.0	400.0	400.0	25.0	10.0	1200.0	48.3	0.0	0.0	0.0	0.0	35.0	50.0
17	44.9	2360.0	180.0	180.0	400.0	400.0	10.0	10.0	1200.0	51.6	0.0	20.0	0.0	20.0	50.0	50.0
18	48.3	2335.0	180.0	135.0	400.0	400.0	10.0	10.0	1200.0	55.5	0.0	45.0	0.0	45.0	50.0	50.0
19	44.5	1695.0	36.0	36.0	323.0	80.0	10.0	10.0	1200.0	51.1	144.0	144.0	77.0	320.0	50.0	50.0
20	45.0	1425.0	36.0	36.0	80.0	80.0	10.0	10.0	1173.0	51.8	144.0	144.0	320.0	320.0	50.0	50.0
21	55.0	1295.0	36.0	36.0	80.0	80.0	10.0	10.0	1043.0	63.3	144.0	144.0	320.0	320.0	50.0	50.0
22	59.4	955.0	36.0	36.0	80.0	80.0	10.0	10.0	703.0	68.3	144.0	144.0	320.0	0.0	0.0	0.0
23	55.0	530.0	36.0	36.0	80.0	80.0	10.0	10.0	278.0	63.3	144.0	144.0	320.0	316.0	0.0	0.0
24	50.7	425.0	36.0	36.0	80.0	80.0	10.0	10.0	173.0	58.3	144.0	144.0	236.0	0.0	0.0	0.0

Table 9. Cogeneration with r = 1. Thermal quantities.

Hours [h]	$P_{D_{th_t}}$ [kW_{th}]	$P_{C_{th_{t,1}}}$ [kW_{th}]	$P_{C_{th_{t,2}}}$ [kW_{th}]	$P_{C_{th_{t,3}}}$ [kW_{th}]	$P_{C_{th_{t,4}}}$ [kW_{th}]	P_{Bt} [kW_{th}]
1	320	265.0	100.0	12.5	12.5	0.0
2	295	195.0	100.0	12.5	12.5	0.0
3	275	170.0	100.0	12.5	12.5	0.0
4	275	150.0	100.0	12.5	12.5	0.0
5	495	150.0	100.0	12.5	12.5	0.0
6	605	150.0	100.0	12.5	12.5	0.0
7	1305	370.0	100.0	12.5	12.5	0.0
8	3560	480.0	100.0	75.0	75.0	200.0
9	3570	500.0	500.0	75.0	75.0	2410.0
10	3690	500.0	500.0	75.0	75.0	2540.0
11	3625	500.0	500.0	75.0	75.0	2475.0
12	4095	500.0	500.0	75.0	75.0	2945.0
13	4125	500.0	500.0	75.0	75.0	2975.0
14	4300	500.0	500.0	75.0	75.0	3150.0
15	4255	500.0	500.0	75.0	75.0	3105.0
16	3950	500.0	500.0	75.0	75.0	2800.0
17	3905	500.0	500.0	75.0	75.0	2755.0
18	3605	500.0	500.0	75.0	75.0	1455.0
19	1695	500.0	500.0	75.0	75.0	1455.0
20	1680	500.0	500.0	75.0	75.0	545.0
21	1425	500.0	500.0	75.0	75.0	530.0
22	1020	500.0	500.0	75.0	75.0	275.0
23	520	500.0	495.0	12.5	12.5	0.0
24	390	395.0	100.0	12.5	12.5	0.0

Table 10. Technical characteristics of the shiftable loads.

			$D_{SH_{t,j}}$				
Loads	Devices	S_j [h]	[kW] s_1	[kW] s_2	[kW] s_3	T_j [h]	T_j^{st}
1	Washing machine	2	49.5	39.6		24	19
2	Washing and dryer	3	94.5	75.6	283.6	24	19
3	Dishwasher	2	201.6	201.6		24	22
4	Air condition	3	57.6	57.6	57.6	3	10
5	Iron	1	340			3	19
6	Coffee maker	1	44.8			4	7

maximization of the difference between revenue and costs. If Pe_{gridt} is internal to its definition domain before and after the shift, the power generated is always the same, since the shift does not in the link between marginal costs and prices (see Table 13). All changes linked to the shift are, then, absorbed by changes in Pe_{gridt}. This does not happen if the exchanged power reaches its maximum (see Table 15). When r = 0, all the loads shift so as to

Table 11. Composition of the shiftable loads.

Loads	Devices	$d_{SH_{t,j}}$ [kW] s_1	[kW] s_2	[kW] s_3	N_j
1	Washing machine	0.5	0.4		99
2	Washing and dryer	0.5	0.4	1.2	189
3	Dishwasher	0.7	0.7		288
4	Air condition	0.2	0.2	0.2	288
5	Iron	1			340
6	Coffee maker	0.8			56

minimize the cost of electricity purchase; when r = 1, each load estimates if it is more convenient to shift in the intervals in which the cost is minimized or in the intervals in which the revenue from the sale in reserve market is maximized. So, when r = 0, the load 4 (air conditioners) shifts in the intervals 16–18 to which corresponds the minimum cost; when r = 1, it does not shift because the revenue that is obtained if it stays where it is (equal to 2592) is bigger than the saving (equal to 2240) obtained if it would shift in 16–18 h.

In addition to the mentioned case, it is also considered the case in which the probability is not constant, assuming the value 0 or 1 depending of the interval Tables 16 and 17. Now that, with the shift, intertemporal constraints were introduced, it makes sense to consider that there are intervals in which r_t is very high and in intervals in which it is very low.

Let it show that load 4 shifts as the case 5.

Cogeneration and storage system

Finally, one only centralized electric storage unit, with a power rating of 500 kW and a maximum stored energy of 4500 kWh, is assumed available. From a qualitative point of view, nothing changes. The storage and the shift work in the same way, compatibly with their respective different constraints (essentially, for the storage, the restoration of level and, for the shift, T_j and S_j constraints).

Table 18 reports the value of the daily management costs of the MG in all of cases that were considered. The table reports the percentage variations of the total costs for cases 2–9 with respect to the case 1. The presence of storage leads to lower costs by bringing more edibility to model. In absence of regulation, the arbitrage could be admitted. The arbitrage is the simultaneous purchase and sale of energy to profit from a difference in the price. If it happens, the units continue to be produced according to the marginal cost criteria, obtaining the same previous results, but the amount of energy exchanged with the main grid Pe_{gridt} changes. In fact, MG buys in the electricity market, for each hour, the maximum quantity of energy admissible according to the constraints in order to sell the highest quantity of energy into the reserve market. This, as shown in equation (1), requires that, in the model, the powers $P^r_{Gt,j}$ and $P^r_{Cet,j}$ P are limited from above by the difference between the maximum power and the minimum power rather than the difference between the maximum power and the power produced. In Table 19 are reported the results for some cases considered.

Table 12. Cogeneration and shift with r = 0. Shiftable and shifted loads.

Hours [h]	P^e [€]	$P_{D_{F_t}}$ [kW$_e$]	$D_{SH_{t,1}}$ [kW$_e$]	$D_{SH_{t,2}}$ [kW$_e$]	$D_{SH_{t,3}}$ [kW$_e$]	$D_{SH_{t,4}}$ [kW$_e$]	$D_{SH_{t,5}}$ [kW$_e$]	$D_{SH_{t,6}}$ [kW$_e$]	$P_{D_{SH_{t,1}}}$ [kW$_e$]	$P_{D_{SH_{t,2}}}$ [kW$_e$]	$P_{D_{SH_{t,3}}}$ [kW$_e$]	$P_{D_{SH_{t,4}}}$ [kW$_e$]	$P_{D_{SH_{t,5}}}$ [kW$_e$]	$P_{D_{SH_{t,6}}}$ [kW$_e$]	$P'D_{e_t}$ [kW$_e$]
1	41.7	440.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	440.0
2	39.7	440.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	440.0
3	38.0	440.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	440.0
4	36.0	440.0	0.0	0.0	0.0	0.0	0.0	0.0	49.5	94.5	201.6	0.0	0.0	0.0	785.6
5	36.0	440.0	0.0	0.0	0.0	0.0	0.0	0.0	39.6	75.6	201.6	0.0	0.0	0.0	756.8
6	36.0	740.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	283.5	0.0	0.0	0.0	0.0	1023.5
7	39.8	1200.0	0.0	0.0	0.0	0.0	0.0	44.8	0.0	0.0	0.0	0.0	0.0	44.8	1200.0
8	44.6	1905.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1905.0
9	49.5	2345.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2345.0
10	51.8	2405.0	0.0	0.0	0.0	57.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2357.4
11	46.3	2420.0	0.0	0.0	0.0	57.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2362.4
12	40.8	2440.0	0.0	0.0	0.0	57.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2382.4
13	39.3	2470.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2470.0
14	38.5	2465.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2465.0
15	43.7	2450.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2450.0
16	42.0	2395.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	57.6	0.0	0.0	2452.6
17	44.9	2360.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	57.6	0.0	0.0	2417.6
18	48.3	2335.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	57.6	0.0	0.0	2392.6
19	44.5	1210.0	49.5	94.5	0.0	0.0	340.0	0.0	0.0	0.0	0.0	0.0	340.0	0.0	1551.0
20	45.0	1309.8	39.6	75.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1309.8
21	55.0	1011.5	0.0	283.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1011.5
22	59.4	753.4	0.0	0.0	201.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	753.4
23	55.0	328.4	0.0	0.0	201.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	328.4
24	50.7	425.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	425.0

Table 13. Cogeneration and shift with r = 0. Post shift state.

Hours [h]	$P^t_{D_{et}}$ [kWe]	$P^e_{G_{1t}}$ [kWe]	$P^e_{G_{2t}}$ [kWe]	$P^e_{ce_{1t}}$ [kWe]	$P^e_{ce_{2t}}$ [kWe]	$P^e_{ce_{3t}}$ [kWe]	$P^e_{ce_{4t}}$ [kWe]	$P^e_{grid_t}$ [kWe]	$P_{D_{th_t}}$ [kWth]	$P_{Ce_{1\,th_t}}$ [kWth]	$P_{Ce_{2\,th_t}}$ [kWth]	$P_{Ce_{3\,th_t}}$ [kWth]	$P_{Ce_{4\,th_t}}$ [kWth]	P_{B_t} [kWth]
1	440	180.0	180.0	212.0	80.0	10.0	10.0	−232.0	390.0	265.0	100.0	12.5	12.5	0.0
2	440	180.0	180.0	156.0	80.0	10.0	10.0	−176.0	320.0	195.0	100.0	12.5	12.5	0.0
3	440	180.0	180.0	136.0	80.0	10.0	10.0	−156.0	295.0	170.0	100.0	12.5	12.5	0.0
4	440	180.0	180.0	120.0	80.0	10.0	10.0	205.6	275.0	150.0	100.0	12.5	12.5	0.0
5	440	180.0	180.0	120.0	80.0	10.0	10.0	176.8	275.0	150.0	100.0	12.5	12.5	0.0
6	740	180.0	180.0	296.0	80.0	10.0	10.0	267.5	495.0	370.0	100.0	12.5	12.5	0.0
7	1200	180.0	180.0	384.0	80.0	10.0	10.0	356.0	605.0	480.0	100.0	12.5	12.5	0.0
8	1905	180.0	180.0	400.0	400.0	60.0	60.0	625.0	1305.0	500.0	500.0	75.0	75.0	200.0
9	2345	180.0	180.0	400.0	400.0	60.0	60.0	1065.0	3560.0	500.0	500.0	75.0	75.0	2410.0
10	2405	180.0	180.0	400.0	400.0	60.0	60.0	1067.4	3570.0	500.0	500.0	75.0	75.0	2540.0
11	2420	180.0	180.0	400.0	400.0	60.0	60.0	1082.4	3690.0	500.0	500.0	75.0	75.0	2475.0
12	2440	180.0	180.0	400.0	400.0	60.0	60.0	1102.4	3625.0	500.0	500.0	75.0	75.0	2945.0
13	2470	180.0	180.0	400.0	400.0	60.0	60.0	1190.0	4095.0	500.0	500.0	75.0	75.0	2975.0
14	2465	180.0	180.0	400.0	400.0	60.0	60.0	1185.0	4125.0	500.0	500.0	75.0	75.0	3150.0
15	2450	180.0	180.0	400.0	400.0	60.0	60.0	1170.0	4300.0	500.0	500.0	75.0	75.0	3105.0
16	2395	180.0	180.0	400.0	400.0	60.0	60.0	1172.6	4255.0	500.0	500.0	75.0	75.0	2800.0
17	2360	180.0	180.0	400.0	400.0	60.0	60.0	1137.6	3950.0	500.0	500.0	75.0	75.0	2755.0
18	2335	180.0	180.0	400.0	400.0	60.0	60.0	1112.6	3905.0	500.0	500.0	75.0	75.0	1455.0
19	1695	180.0	180.0	400.0	400.0	60.0	60.0	271.0	3605.0	500.0	500.0	75.0	75.0	1455.0
20	1425	180.0	180.0	400.0	400.0	60.0	60.0	29.8	1695.0	500.0	500.0	75.0	75.0	545.0
21	1295	180.0	180.0	400.0	400.0	60.0	60.0	−268.5	1680.0	500.0	500.0	75.0	75.0	530.0
22	955	180.0	180.0	400.0	400.0	60.0	60.0	−526.6	1425.0	500.0	500.0	75.0	75.0	275.0
23	530	180.0	180.0	400.0	396.0	10.0	10.0	−847.6	1020.0	500.0	495.0	12.5	12.5	0.0
24	425	180.0	180.0	316.0	80.0	10.0	10.0	−351.0	520.0	395.0	100.0	12.5	12.5	0.0

Table 14. Cogeneration and shift with r = 1. Shiftable and shifted loads.

Hours [h]	$P^e[\in]$	P_{D_F} [kW$_e$]	$D_{SH_{t,1}}$ [kW$_e$]	$D_{SH_{t,2}}$ [kW$_e$]	$D_{SH_{t,3}}$ [kW$_e$]	$D_{SH_{t,4}}$ [kW$_e$]	$D_{SH_{t,5}}$ [kW$_e$]	$D_{SH_{t,6}}$ [kW$_e$]	P_{De_t} [kW$_e$]	$P_{D_{SH_{t,1}}}$ [kW$_e$]	$P_{D_{SH_{t,2}}}$ [kW$_e$]	$P_{D_{SH_{t,3}}}$ [kW$_e$]	$P_{D_{SH_{t,4}}}$ [kW$_e$]	$P_{D_{SH_{t,5}}}$ [kW$_e$]	$P_{D_{SH_{t,6}}}$ [kW$_e$]	$P'D_{e_t}$ [kW$_e$]
1	41.7	440.0	0.0	0.0	0.0	0.0	0.0	0.0	440.0	0.0	0.0	0.0	0.0	0.0	0.0	440.0
2	39.7	440.0	0.0	0.0	0.0	0.0	0.0	0.0	440.0	0.0	0.0	0.0	0.0	0.0	0.0	440.0
3	38.0	440.0	0.0	0.0	0.0	0.0	0.0	0.0	440.0	0.0	0.0	0.0	0.0	0.0	0.0	440.0
4	36.0	440.0	0.0	0.0	0.0	0.0	0.0	0.0	440.0	49.5	94.5	201.6	0.0	0.0	0.0	785.6
5	36.0	440.0	0.0	0.0	0.0	0.0	0.0	0.0	440.0	39.6	75.6	201.6	0.0	0.0	0.0	756.8
6	36.0	740.0	0.0	0.0	0.0	0.0	0.0	0.0	740.0	0.0	283.5	0.0	0.0	0.0	0.0	1023.5
7	39.8	1152.2	0.0	0.0	0.0	0.0	0.0	44.8	1200.0	0.0	0.0	0.0	0.0	0.0	44.8	1200.0
8	44.6	1905.0	0.0	0.0	0.0	0.0	0.0	0.0	1905.0	0.0	0.0	0.0	0.0	0.0	0.0	1905.0
9	49.5	2345.0	0.0	0.0	0.0	0.0	0.0	0.0	2345.0	0.0	0.0	0.0	0.0	0.0	0.0	2345.0
10	51.8	2347.4	0.0	0.0	0.0	57.6	0.0	0.0	2405.0	0.0	0.0	0.0	0.0	0.0	0.0	2405.0
11	46.3	2362.4	0.0	0.0	0.0	57.6	0.0	0.0	2420.0	0.0	0.0	0.0	0.0	0.0	0.0	2420.0
12	40.8	2382.4	0.0	0.0	0.0	0.0	0.0	0.0	2440.0	0.0	0.0	0.0	0.0	0.0	0.0	2440.0
13	39.3	2470.0	0.0	0.0	0.0	0.0	0.0	0.0	2470.0	0.0	0.0	0.0	0.0	0.0	0.0	2470.0
14	38.5	2465.0	0.0	0.0	0.0	0.0	0.0	0.0	2465.0	0.0	0.0	0.0	0.0	0.0	0.0	2465.0
15	43.7	2450.0	0.0	0.0	0.0	0.0	0.0	0.0	2450.0	0.0	0.0	0.0	0.0	0.0	0.0	2450.0
16	42.0	2395.0	0.0	0.0	0.0	0.0	0.0	0.0	2395.0	0.0	0.0	0.0	57.6	0.0	0.0	2395.0
17	44.9	2360.0	0.0	0.0	0.0	0.0	0.0	0.0	2360.0	0.0	0.0	0.0	57.6	0.0	0.0	2360.0
18	48.3	2335.0	0.0	0.0	0.0	0.0	0.0	0.0	2335.0	0.0	0.0	0.0	57.6	0.0	0.0	2335.0
19	44.5	1211.0	49.5	94.5	0.0	0.0	340.0	0.0	1695.0	0.0	0.0	0.0	0.0	340.0	0.0	1551.0
20	45.0	1309.8	39.6	75.6	0.0	0.0	0.0	0.0	1425.0	0.0	0.0	0.0	0.0	0.0	0.0	1309.8
21	55.0	1011.5	0.0	283.5	0.0	0.0	0.0	0.0	1295.0	0.0	0.0	0.0	0.0	0.0	0.0	1011.5
22	59.4	753.4	0.0	0.0	201.6	0.0	0.0	0.0	955.0	0.0	0.0	0.0	0.0	0.0	0.0	753.4
23	55.0	328.4	0.0	0.0	201.6	0.0	0.0	0.0	530.0	0.0	0.0	0.0	0.0	0.0	0.0	328.4
24	50.7	425.0	0.0	0.0	0.0	0.0	0.0	0.0	425.0	0.0	0.0	0.0	0.0	0.0	0.0	425.0

Table 15. Cogeneration and shift with r = 1. Post shift state.

Hours [h]	$P^t_{D_{et}}$ [kW$_e$]	$P^e_{G_{t,1}}$ [kW$_e$]	$P^e_{G_{t,2}}$ [kW$_e$]	$P^e_{ce_{t,1}}$ [kW$_e$]	$P^e_{ce_{t,2}}$ [kW$_e$]	$P^e_{ce_{t,3}}$ [kW$_e$]	$P^e_{ce_{t,4}}$ [kW$_e$]	$P^e_{grid_t}$ [kW$_e$]	$P^r_{G_{t,1}}$ [kW$_e$]	$P^r_{G_{t,2}}$ [kW$_e$]	$P^r_{Ce_{t,1}}$ [kW$_e$]	$P^r_{Ce_{t,2}}$ [kW$_e$]	$P^r_{Ce_{t,3}}$ [kW$_e$]	$P^r_{Ce_{t,4}}$ [kW$_e$]	$P^r_{grid_t}$ [kW$_{th}$]	$P_{D_{th}}$ [kW$_{th}$]	$P_{Ceth_{t,1}}$ [kW$_{th}$]	$P_{Ceth_{t,2}}$ [kW$_{th}$]	$P_{Ceth_{t,3}}$ [kW$_{th}$]
1	440.0	36.0	36.0	80.0	80.0	10.0	10.0	188.0	48.0	144.0	144.0	132.0	0.0	0.0	0.0	390.0	265.0	100.0	12.5
2	440.0	36.0	36.0	80.0	80.0	10.0	10.0	188.0	45.0	144.0	144.0	76.0	0.0	0.0	0.0	320.0	195.0	100.0	12.5
3	440.0	36.0	36.0	80.0	80.0	10.0	10.0	188.0	43.8	144.0	144.0	56.0	0.0	0.0	0.0	295.0	170.0	100.0	12.5
4	785.6	36.0	36.0	80.0	80.0	10.0	10.0	533.6	41.4	144.0	144.0	40.0	0.0	0.0	0.0	275.0	150.0	100.0	12.5
5	756.8	36.0	36.0	80.0	80.0	10.0	10.0	504.8	41.5	144.0	144.0	40.0	0.0	0.0	0.0	275.0	150.0	100.0	12.5
6	1023.5	36.0	36.0	80.0	80.0	10.0	10.0	771.5	41.4	144.0	144.0	216.0	0.0	0.0	0.0	495.0	370.0	100.0	12.5
7	1200.0	36.0	36.0	80.0	80.0	10.0	10.0	948.0	45.8	144.0	144.0	304.0	0.0	0.0	0.0	605.0	480.0	100.0	12.5
8	1905.0	36.0	145.0	400.0	213.0	10.0	10.0	1200.0	51.3	144.0	144.0	0.0	187.0	50.0	50.0	1350.0	500.0	500.0	75.0
9	2345.0	180.0	180.0	400.0	400.0	10.0	10.0	1200.0	56.9	0.0	0.0	0.0	35.0	50.0	135.0	3560.0	500.0	500.0	75.0
10	2405.0	180.0	180.0	400.0	400.0	35.0	10.0	1200.0	59.6	0.0	0.0	0.0	0.0	25.0	50.0	3690.0	500.0	500.0	75.0
11	2420.0	180.0	180.0	400.0	400.0	50.0	10.0	1200.0	53.3	0.0	0.0	0.0	0.0	10.0	50.0	3625.0	500.0	500.0	75.0
12	2440.0	180.0	180.0	400.0	400.0	50.0	20.0	1200.0	47.0	0.0	0.0	0.0	0.0	0.0	50.0	4095.0	500.0	500.0	75.0
13	2470.0	180.0	180.0	400.0	400.0	60.0	60.0	1200.0	45.2	0.0	0.0	0.0	0.0	0.0	10.0	4125.0	500.0	500.0	75.0
14	2465.0	180.0	180.0	400.0	400.0	60.0	35.0	1200.0	44.2	0.0	0.0	0.0	0.0	0.0	15.0	4300.0	500.0	500.0	75.0
15	2450.0	180.0	180.0	400.0	400.0	60.0	30.0	1200.0	50.2	0.0	0.0	0.0	0.0	0.0	30.0	4255.0	500.0	500.0	75.0
16	2395.0	180.0	180.0	400.0	400.0	25.0	10.0	1200.0	48.3	0.0	0.0	0.0	0.0	35.0	50.0	3950.0	500.0	500.0	75.0
17	2360.0	180.0	180.0	400.0	400.0	10.0	10.0	1200.0	51.6	0.0	20.0	0.0	20.0	50.0	50.0	3905.0	500.0	500.0	75.0
18	2335.0	180.0	135.0	400.0	400.0	10.0	60.0	1200.0	55.5	0.0	0.0	0.0	45.0	50.0	50.0	2605.0	500.0	500.0	75.0
19	1551.0	36.0	36.0	323.0	80.0	10.0	10.0	1056.0	51.2	144.0	144.0	77.0	320.0	50.0	50.0	2605.0	500.0	500.0	75.0
20	1309.8	36.0	36.0	80.0	80.0	10.0	10.0	1057.8	51.8	144.0	144.0	320.0	320.0	50.0	50.0	1695.0	500.0	500.0	75.0
21	1011.5	36.0	36.0	80.0	80.0	10.0	10.0	759.5	144.0	144.0	320.0	320.0	50.0	50.0	0.0	1680.0	500.0	500.0	75.0
22	753.4	36.0	36.0	80.0	80.0	10.0	10.0	501.4	68.3	144.0	144.0	320.0	320.0	50.0	50.0	1425.0	500.0	500.0	75.0
23	328.4	180.0	180.0	400.0	396.0	10.0	10.0	75.4	63.3	144.0	144.0	320.0	316.0	0.0	0.0	1020.0	500.0	495.0	12.5
24	425.0	36.0	36.0	80.0	80.0	10.0	10.0	173.0	58.3	144.0	144.0	236.0	0.0	0.0	0.0	520.0	395.0	100.0	12.5

Table 16. Cogeneration and shift with r = 0/1. Shiftable and shifted loads.

Hour [h]	ρ^e[€]	r_t[%]	P_{D_F} [kW$_e$]	$D_{SH_{t,1}}$ [kW$_e$]	$D_{SH_{t,2}}$ [kW$_e$]	$D_{SH_{t,3}}$ [kW$_e$]	$D_{SH_{t,4}}$ [kW$_e$]	$D_{SH_{t,5}}$ [kW$_e$]	$D_{SH_{t,6}}$ [kW$_e$]	P_{De_t} [kW$_e$]	$P_{D_{SH_{t,1}}}$ [kW$_e$]	$P_{D_{SH_{t,2}}}$ [kW$_e$]	$P_{D_{SH_{t,3}}}$ [kW$_e$]	$P_{D_{SH_{t,4}}}$ [kW$_e$]	$P_{D_{SH_{t,5}}}$ [kW$_e$]	$P_{D_{SH_{t,6}}}$ [kW$_e$]	$P'D_{e_t}$ [kW$_e$]
1	41.7	0.0	440.0	0.0	0.0	0.0	0.0	0.0	0.0	440.0	0.0	0.0	0.0	0.0	0.0	0.0	440.0
2	39.7	0.0	440.0	0.0	0.0	0.0	0.0	0.0	0.0	440.0	0.0	0.0	0.0	0.0	0.0	0.0	440.0
3	38	0.0	440.0	0.0	0.0	0.0	0.0	0.0	0.0	440.0	0.0	0.0	0.0	0.0	0.0	0.0	440.0
4	36	0.0	440.0	0.0	0.0	0.0	0.0	0.0	0.0	440.0	49.5	94.5	201.6	0.0	0.0	0.0	785.6
5	36	0.0	440.0	0.0	0.0	0.0	0.0	0.0	0.0	440.0	39.6	75.6	201.6	0.0	0.0	0.0	756.8
6	36	1.0	740.0	0.0	0.0	0.0	0.0	0.0	0.0	740.0	0.0	283.5	0.0	0.0	0.0	0.0	1023.5
7	39.8	1.0	1152.2	0.0	0.0	0.0	0.0	0.0	44.8	1200.0	0.0	0.0	0.0	0.0	0.0	0.0	1200.0
8	44.6	1.0	1905.0	0.0	0.0	0.0	0.0	0.0	0.0	1905.0	0.0	0.0	0.0	0.0	0.0	0.0	1905.0
9	49.5	1.0	2345.0	0.0	0.0	0.0	0.0	0.0	0.0	2345.0	0.0	0.0	0.0	0.0	0.0	0.0	2345.0
10	51.8	0.0	2347.4	0.0	0.0	0.0	57.6	0.0	0.0	2405.0	0.0	0.0	0.0	0.0	0.0	0.0	2405.0
11	46.3	0.0	2362.4	0.0	0.0	0.0	57.6	0.0	0.0	2420.0	0.0	0.0	0.0	0.0	0.0	0.0	2420.0
12	40.8	0.0	2382.4	0.0	0.0	0.0	57.6	0.0	0.0	2440.0	0.0	0.0	0.0	0.0	0.0	0.0	2440.0
13	39.3	0.0	2470.0	0.0	0.0	0.0	0.0	0.0	0.0	2470.0	0.0	0.0	0.0	0.0	0.0	0.0	2470.0
14	38.5	0.0	2465.0	0.0	0.0	0.0	0.0	0.0	0.0	2465.0	0.0	0.0	0.0	0.0	0.0	0.0	2465.0
15	43.7	1.0	2450.0	0.0	0.0	0.0	0.0	0.0	0.0	2450.0	0.0	0.0	0.0	0.0	0.0	0.0	2450.0
16	42	1.0	2395.0	0.0	0.0	0.0	0.0	0.0	0.0	2395.0	0.0	0.0	0.0	57.6	0.0	0.0	2395.0
17	44.9	1.0	2360.0	0.0	0.0	0.0	0.0	0.0	0.0	2360.0	0.0	0.0	0.0	57.6	0.0	0.0	2360.0
18	48.3	0.0	2335.0	0.0	0.0	0.0	0.0	0.0	0.0	2335.0	0.0	0.0	0.0	57.6	0.0	0.0	2335.0
19	44.5	0.0	1211.0	49.5	94.5	0.0	0.0	340.0	0.0	1695.0	0.0	0.0	0.0	0.0	340.0	0.0	1551.0
20	45	0.0	1309.8	39.6	75.6	0.0	0.0	0.0	0.0	1425.0	0.0	0.0	0.0	0.0	0.0	0.0	1309.8
21	55	0.0	1011.5	0.0	283.5	0.0	0.0	0.0	0.0	1295.0	0.0	0.0	0.0	0.0	0.0	0.0	1011.5
22	59.4	0.0	753.4	0.0	0.0	201.6	0.0	0.0	0.0	955.0	0.0	0.0	0.0	0.0	0.0	0.0	753.4
23	55	0.0	328.4	0.0	0.0	201.6	0.0	0.0	0.0	530.0	0.0	0.0	0.0	0.0	0.0	0.0	328.4
24	50.7	0.0	425.0	0.0	0.0	0.0	0.0	0.0	0.0	425.0	0.0	0.0	0.0	0.0	0.0	0.0	425.0

Table 17. Cogeneration and shift with r = 0/1. Post shift state.

Hour [h]	P_{D_F} [kW$_e$]	$P^e_{G_{t,1}}$ [kW$_e$]	$P^e_{G_{t,2}}$ [kW$_e$]	$P^e_{ce_{t,1}}$ [kW$_e$]	$P^e_{ce_{t,2}}$ [kW$_e$]	$P^e_{ce_{t,3}}$ [kW$_e$]	$P^e_{ce_{t,4}}$ [kW$_e$]	$P^e_{grid_t}$ [kW$_e$]	$P^r_{G_{t,1}}$ [kW$_e$]	$P^r_{G_{t,2}}$ [kW$_e$]	$P^r_{Ce_{t,1}}$ [kW$_e$]	$P^r_{Ce_{t,2}}$ [kW$_e$]	$P^r_{Ce_{t,3}}$ [kW$_e$]	$P^r_{Ce_{t,4}}$ [kW$_e$]	$P^r_{grid_t}$ [kW$_e$]	$P_{D_{th_t}}$ [kW$_{th}$]	$P_{Ce_{th_{t,1}}}$ [kW$_{th}$]	$P_{Ce_{th_{t,2}}}$ [kW$_{th}$]	$P_{Ce_{th_{t,3}}}$ [kW$_{th}$]
1	440.0	180.0	180.0	212.0	80.0	10.0	10.0	−232.0	0.0	0.0	0.0	0.0	0.0	0.0		390.0	265.0	100.0	12.5
2	440.0	180.0	180.0	156.0	80.0	10.0	10.0	−176.0	0.0	0.0	0.0	0.0	0.0	0.0		320.0	195.0	100.0	12.5
3	440.0	180.0	180.0	136.0	80.0	10.0	10.0	−156.0	0.0	0.0	0.0	0.0	0.0	0.0		295.0	170.0	100.0	12.5
4	440.0	180.0	180.0	120.0	80.0	10.0	10.0	205.6	0.0	0.0	0.0	0.0	0.0	0.0		275.0	150.0	100.0	12.5
5	440.0	180.0	180.0	120.0	80.0	10.0	10.0	176.8	0.0	0.0	0.0	0.0	0.0	0.0		275.0	150.0	100.0	12.5
6	740.0	36.0	36.0	80.0	80.0	10.0	10.0	771.5	144.0	144.0	216.0	0.0	0.0	0.0		495.0	370.0	100.0	12.5
7	1152.2	36.0	36.0	80.0	80.0	10.0	10.0	948.0	144.0	144.0	304.0	0.0	0.0	0.0		605.0	480.0	100.0	12.5
8	1905.0	36.0	36.0	400.0	213.0	10.0	10.0	1200.0	144.0	144.0	0.0	187.0	50.0	50.0		1350.0	500.0	500.0	75.0
9	2345.0	180.0	145.0	400.0	400.0	10.0	10.0	1200.0	0.0	0.0	0.0	35.0	50.0	135.0		3560.0	500.0	500.0	75.0
10	2347.4	180.0	180.0	400.0	400.0	60.0	60.0	1067.4	0.0	0.0	0.0	0.0	0.0	0.0		3690.0	500.0	500.0	75.0
11	2362.4	180.0	180.0	400.0	400.0	60.0	60.0	1082.4	0.0	0.0	0.0	0.0	0.0	0.0		3625.0	500.0	500.0	75.0
12	2382.4	180.0	180.0	400.0	400.0	60.0	60.0	1102.4	0.0	0.0	0.0	0.0	0.0	0.0		4095.0	500.0	500.0	75.0
13	2470.0	180.0	180.0	400.0	400.0	60.0	60.0	1190.0	0.0	0.0	0.0	0.0	0.0	0.0		4125.0	500.0	500.0	75.0
14	2465.0	180.0	180.0	400.0	400.0	60.0	60.0	1185.0	0.0	0.0	0.0	0.0	0.0	0.0		4300.0	500.0	500.0	75.0
15	2450.0	180.0	180.0	400.0	400.0	60.0	30.0	1200.0	0.0	0.0	0.0	0.0	0.0	30.0		4255.0	500.0	500.0	75.0
16	2395.0	180.0	180.0	400.0	400.0	60.0	32.6	1200.0	0.0	0.0	0.0	0.0	0.0	32.6		3950.0	500.0	500.0	75.0
17	2360.0	180.0	180.0	400.0	400.0	47.6	10.0	1200.0	0.0	0.0	0.0	0.0	12.4	50.0		3905.0	500.0	500.0	75.0
18	2335.0	180.0	180.0	400.0	400.0	60.0	60.0	1112.6	0.0	0.0	0.0	0.0	0.0	0.0		2605.0	500.0	500.0	75.0
19	1211.0	180.0	180.0	400.0	400.0	60.0	60.0	271.0	0.0	0.0	0.0	0.0	0.0	0.0		2605.0	500.0	500.0	75.0
20	1309.8	180.0	180.0	400.0	400.0	60.0	60.0	29.8	0.0	0.0	0.0	0.0	0.0	0.0		1695.0	500.0	500.0	75.0
21	1011.5	180.0	180.0	400.0	400.0	60.0	60.0	−268.5	0.0	0.0	0.0	0.0	0.0	0.0		1680.0	500.0	500.0	75.0
22	753.4	180.0	180.0	400.0	400.0	60.0	60.0	−526.6	0.0	0.0	0.0	0.0	0.0	0.0		1425.0	500.0	500.0	75.0
23	328.4	180.0	180.0	400.0	396.0	10.0	10.0	−847.6	0.0	0.0	0.0	0.0	0.0	0.0		1020.0	500.0	495.0	12.5
24	425.0	180.0	180.0	316.0	80.0	10.0	10.0	−351.0	0.0	0.0	0.0	0.0	0.0	0.0		520.0	395.0	100.0	12.5

Table 18. Daily management costs—no arbitrage.

Case study	OF [€]	Boiler cost [€]	Total cost [€]	Variation (%)
Case_1	490.2	1735.8	2226.0	
Case_2	324.2	1735.8	2060.0	−7.5
Case_3	1879.0		1879.0	−15.6
Case_4	1675.0		1675.0	−24.8
Case_5	1590.0		1590.0	−28.6
Case_6	1349.0		1349.0	−39.4
Case_7	1470.0		1470.0	−34.0
Case_8	1006.0		1006.0	−54.8
Case_9	870.0		870.0	−61.0

Table 19. Daily management costs with arbitrage.

Case study	Total cost [€]	Variation (%)
Case 2	1859.0	−9.8
Case 4	1430.0	−15.6
Case 6	1120.0	−18.3
Case 8	787.0	−21.8

Conclusions

The paper focused on the participation of an MG in both day-ahead energy and reserve spinning market. It was shown how the MG solves a decision-making problem about the development of an optimal bidding strategy for both markets, evaluating different risk tolerances (adverse, neutral, and incline).

An MG is considered in which both thermal and electrical loads must be satisfied, so that in the MG only electricity power plants, CHP plants, and heat production plants (boilers) were already installed. The presence of thermal and electrical storage systems is also accounted for. Moreover, it was considered that both generators and loads can take part in the reserve market. The demand participation happens through both shiftable and curtailable loads.

In this work the bidding strategy is limited to the submission, in the day-ahead electricity markets, of the only one value of the optimal hourly powers exchanged with the main grid, obtained in correspondence to the most probably hourly market profiles.

The paper showed the implementation of a new joint approach to take part in to the day-ahead market and spinning reserve market, formulated by a detailed mathematical optimization model. It is written in the most general form as possible, allows to obtain the optimal values of power to offer in both markets that maximize the difference between revenues and costs, in compliance with all existing technical and operational constraints. Numerical applications of the approach are presented and discussed. The model was implemented for different configurations. It was, first, supposed that all loads are fixed and that all the generation units (cogenerators and generators) produce only electricity, so that only a boiler satisfies the thermal load. In this configuration, cases were considered in which the probability that the reserve is called to produce is very high ($r = 1$) or very low ($r = 0$). It was, then, considered the cogeneration, always assuming the presence only of fixed loads. Also in this configuration, are considered the cases r = 1 and r = 1. Always considering the cogeneration, it was supposed also that a percentage of the loads is shiftable. Now, in addition to cases r = 1, it was also considered the case in which the probability is not constant, being able to assume the value 0 or 1 depending on the interval. It is, finally, examined the case in which is present a storage system. Everything presented and discussed clearly shows the effectiveness of the model.

Future research will focus on the formulation of the optimal bidding curves to present in two markets and on the resolution of the Unit Commitment problem.

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Note

a. The fixed load, for each interval, is curtailed by RES production.

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Appendix

Notation

$C_{B_j}()$	production cost of the jth boiler
$C_{c_j}()$	production cost of the jth cogeneration unit
$C_{D_{CU_j}}()$	curtailment cost of the jth load

$C_{G_j}()$	production cost of the *j*th generation unit
$D_{SH_{t,j}}$	shiftable power of the *j*th load
E (x)	expected value of generic quantity "x"
K_{s_j}	charge/discharge thermal efficiency coefficient
$P_{B_{t,j}}$	thermal power of the *j*th boiler
$P^e_{Ce_{t,j}}$	electric power of the *j*th CHP unit for the energy market
$P^r_{Ce_{t,j}}$	electric power of the *j*th CHP unit for the spinning reserve market
$P^e_{Dcu_{t,j}}$	power curtailable of the *j*th load for energy market
$P^r_{Dcu_{t,j}}$	power curtailable of the *j*th load for spinning reserve market
$P_{DF_{t,j}}$	power of the *j*th electrical fixed load reduced by the amount of electric RES forecasted
$P_{DSH_{t,j}}$	shifted power of the *j*th load
$P_{Dth_{t,j}}$	power of the *j*th thermal fixed load reduced by the amount of electric RES forecasted
$P^e_{grid_t}$	power interchanged with the MV grid for the energy market
$P^r_{grid_t}$	power interchanged with the MV grid for the reserve market
$P^e_{G_{t,j}}$	power of the *j*th unit for the energy market
$P^r_{G_{t,j}}$	power of the *j*th unit for the spinning reserve market
$P_{SE_{t,j}}$	power of the *j*th electrical storage unit
$P_{ST_{t,j}}$	power of the *j*th thermal storage unit
r_t	perceived probability the reserve is called (or not)
s_t	hourly interval of S_j
S_j	cycle duration of the *j*th shiftable load
T_j	time window of the *j*th shiftable load
T^{st}_j	time at which the *j*th shiftable loads starts
$u_{t,j}$	binary variables
$W_{SE_{t,j}}$	level of the *j*th electrical storage unit
$W_{ST_{t,j}}$	level of the *j*th thermal storage unit
α_j	economic coefficient of second order of the j-ma power plants
β	economic coefficient of first order of the j-ma power plants
γ_c	economic constant coefficient
η_j	cogeneration ration
ρ^e_t	energy market price
ρ^r_t	spinning reserve market price
Ω_B	set of boilers
Ω_C	set of cogeneration power plants (CHP)
$\Omega_{D_{CU}}$	set of curtailable electrical loads
Ω_{D_F}	set of fixed electricity loads
$\Omega_{D_{SE}}$	set of electricity storage units
$\Omega_{D_{SH}}$	set of shiftable electrical loads
$\Omega_{D_{ST}}$	set of thermal storage units
$\Omega_{D_{th}}$	set of thermal loads
Ω_G	set of power production plants