Modeling the Cross Impact of Multi-Energy Player's Price Equilibrium in Retail and Wholesale Markets

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Abstract—**Integration of emerging energy resources in distribution level reveals new opportunities for decision makers to coordinate various energy vectors under the concept of multi-energy system (MES). In this paper, the behavior of a multi-energy player (MEP) who can trade more than one energy carrier to enhance operational flexibility of MES has been investigated. MEP participates in retail and wholesale energy markets to maximize its profit. The strategic behavior of MEP in these two markets is modeled as two synchronized bi-level problems. The problem is linearized and solved through CPLEX 12 solver. Numerical results show the behavior of MEP as a prosumer in the electricity market to make a smother demand and price profile. Moreover, the results reveal a mutual effect of local and wholesale equilibrium prices by increasing the market share of MEP.**

Index Terms—**Electricity market, mathematical programming with equilibrium constraints (MPEC), multi-energy player (MEP), multi-energy system (MES).**

NOMENCLATURE

Subscripts

e	Electricity
g	Natural gas
h	Heat
i	Number of LES
j	Number of retailer
k	Number of Genco
t	Time interval

Superscripts

AB	Auxiliary boiler
Agg	Aggregator
Bid	Bidding of electricity consumers
CHP	Combined heat and power
cha	Heat/electric storage charging
$dcha$	Heat/electric storage discharging
E	Equality constraints
ES	Electric storage
EM	Energy market
$Genco$	Generation Company
HS	Heat storage
in	Input energy to MEP, LES, HS or ES
LES	Local energy system
MEP	Multi-energy player
MED	Multi-energy demand
N	Non-equality constraints
$Offer$	Offering of electricity consumers
out	Output energy from MEP, LES, HS, or ES
$Retailer$	Retailer Company

Parameters and Variables

g, G	Amount of natural gas supply
M	Very big parameter for relaxation of primal and dual constraints.
p, P	Amount of electricity generation
q, Q	Amount of heat production
T	Time period
u	Binary variable
λ	Dual variables for equality constraints
$\underline{\mu}, \overline{\mu}$	Dual variables for lower and upper limits in non-equality constraints
ζ	Dual variables for equality constraints in specific time intervals
γ	Charge/discharge rate
η	Efficiency
π, Π	Energy price
κ	Shadow price for energy balance equation of electricity market
$\mathbf{E}$	Vector of equality constraints
$\mathbf{N}$	Vector of non-equality constraints
$\mathbf{T}$	Vector of equality constraints in specific time
$\mathbf{X}$	Vector of decision variables for dual problems

Remark I: An underlined (overlined) variable is used to represent the minimum (maximum) value of that variable.

Remark II: Capital letters denote parameters and small ones denote variables.

I. INTRODUCTION

A. Motivation

The development of distributed energy resource (DER) technologies, e.g. energy converters and storage, has increased the dependency of energy carriers. On the other hand, the establishment of new business environments (e.g., energy markets) and the participation of more players in the energy system's decision-making process have increased the dependency of stakeholders' decision variables. In order to merge all these new situations, the concept of multi-energy systems (MES) has been introduced [1].

MES is integration of various energy carriers (e.g. electricity, natural gas, district heating, etc.) from technical and economical points of view to enable energy interaction in different levels. In such a system, multi-energy players (MEPs) play a crucial role to aggregate local energy systems (LESs) for enhancing the operational flexibility of the system. MEP is defined as an energy player who can trade more than one energy carrier to increases its total profit and mitigates its operational risk [2]. MEP make a link between individual energy markets and, consequently, introduce itself as a flexible resource to market managers.

B. *Literature Review*

The MES consists of some energy elements (e.g. energy converters and storages) and their corresponding energy transmitters. MEP aggregates part of these facilities to maximize its profit and participate in upstream energy markets. In the literature the aggregation of these local energy resources are investigated from economic, technical, and environmental aspects. In [3] an optimal energy scheduling and energy interaction for a set of energy hub is proposed. The model is extended in [4] and an evolutionary method is implemented to increase the accuracy of results and the speed of convergence. Furthermore, in [5] a decentralized control model is proposed for a set of energy hubs to coordinate their operation. A game-based approach among energy hubs for DR provision is suggested in [6]. In order to analyze the impact of a high penetration wind resources on interdependent MES, a robust optimization approach is used in [7]. Numerical results determine the role of the power system to mitigate the uncertainty of wind resources by considering other energy carriers. On the other hand, [8] has shown that it is possible to increase the utilization factor of wind resources in power system operation with MES facilities (e.g., combined heat and power units). In fact, the power system acts as a link between renewable energy resources and MES that can help to decrease the uncertainty of these resources by using the inherent flexibility of MES.

C. *Contribution*

Although many studies have been oriented to model the MES environment, the aggregation of LES under the concept of MEP to participate in electricity wholesale market have not been addressed yet. The aggregation of a set of energy carriers introduce more flexibility to MEP to participate in electricity market and increasing the level of competition in demand side

In this paper, a typical MEP is considered to aggregate a set of LES for participation in electricity wholesale market. In this regard, MEP is an economical energy player who interacts energy carriers with LES based on a leader-follower aggregation framework. Therefore, MEP sends energy criers prices to the LES and receives their energy consumption/production to determine price equilibrium point for each energy carrier.

On the other hand, MEP participate in wholesale electricity market and compete with other energy producers and consumers. The main goal of this paper is investigation the behavior of MEP in retail and wholesale energy interactions and the mutual effect of energy price equilibrium in these two levels. The rest of the extended abstract is organized as follows. In Section II the problem and its solution are described. MEP models are presented in Section III and the electricity market problem is explained in Section IV. A numerical study and concluding remarks are presented in Sections V and VI, respectively.

II. PROBLEM STATEMENT

Fig. 1 shows the energy flow between the MEP, LESs, and the electricity and gas wholesale markets. LESs cooperate in a competitive environment and are coupled by electricity, gas, and heat prices. There is a conflict in the decision making of the MEP and its LESs. This conflict is due to the independent decision making of the MEP who wants to maximize its profit by utilizing the local and grid-bounded energy resources, hence, affecting the energy price equilibrium. This conflict is modeled using bi-level optimization and transformed to a single-level MILP by using duality theory.

Moreover, the MEP participates in the electricity market and competes with generation companies (Gencos) and electricity retail companies (retailers). The independent system operator (ISO) receives the market players' bids/offers and clears the market based on social welfare maximization. The MEP is a strategic player that participates in the electricity market based on market prices and energy exchanges. The participation of the MEP in the electricity market can be modeled using bi-level programming, where the MEP determines its strategy to participate in the electricity market in the upper level. Meanwhile, the ISO clears the market to determine the market price and the share of the MEP in the equilibrium in the lower level, based on its participation strategy.

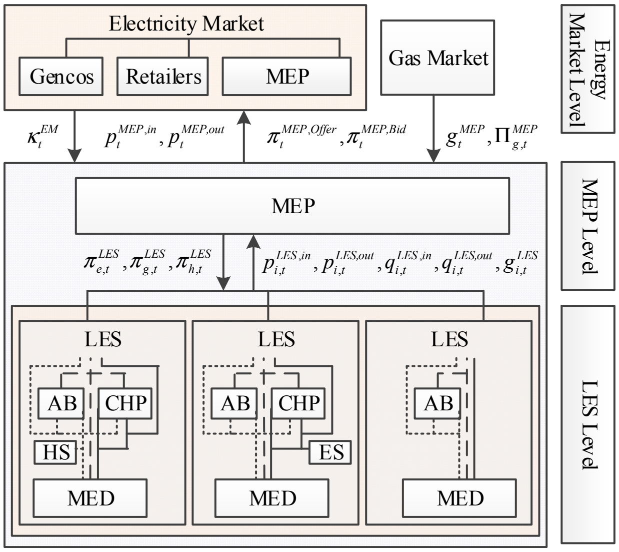

Fig. 1. Interaction of a MEP with LESs and the electricity and gas markets.

The MEP is considered as a price taker in the gas market receiving gas at a predetermined price. Therefore, the MEP interacts energy in two levels simultaneously: with LES including three energy carriers (i.e., electricity, gas, and heat) and with Gencos and retailers in the electricity wholesale market.

III. MEP and LESs Mathematical Model

In this paper the decision making of MEP and LES are modeled based on optimization problems that consist of objective function and constraints.

A. Multi-Energy Player's Decision Making Problem

The MEP receives electricity from the electricity market at its market equilibrium price and natural gas from the gas market at a predetermined price (eq. (1)). It also exchanges electricity, gas, and heat at the equilibrium price with LES. The objective function of the MEP has the following term:

- The cost of MEP operation coming from the electricity procurement from electricity wholesale market;
- The cost of MEP operation coming from the gas procurement from gas wholesale market;
- The incomes of the MEP in distribution level from trading electricity, gas and heat with LES at the aggregation equilibrium prices.

$$
\begin{aligned}
&Max\left\{ f(x)=\sum_t \Big[\Big(-\left(p_t^{MEP,in}-p_t^{MEP,out} \right)\kappa_t^{EM} - g_t^{MEP}\,\Pi_{g,t}^{MEP} \Big) + \right. \\
&\left. \sum_i \Big(\left(p_{i,t}^{LES,in}-p_{i,t}^{LES,out} \right)\pi_{e,i,t}^{Agg} + g_{i,t}^{LES}\pi_{g,i,t}^{Agg} + \left(q_{i,t}^{LES,in}-q_{i,t}^{LES,out} \right)\pi_{h,i,t}^{Agg} \Big) \Big] \right\}
\end{aligned} \tag{1}
$$

In eq. (1) p, g, and q determine the amount of electricity, gas and heat, respectively. Moreover, π and Π show energy prices which capital one denote parameter and small one denote variable.

The MEP operator should maintain the energy balance for electricity, gas and heat (2)-(4). For the gas energy carrier, the maximum amount of gas input to the MEP is shown in (5), which is related to the capacity of its interconnectors to the upstream gas network.

$$\left(p_t^{MEP,in}-p_t^{MEP,out} \right) - \sum_i \left(p_{i,t}^{LES,in}-p_{i,t}^{LES,out} \right) = 0 \tag{2}$$

$$g_t^{MEP} - \sum_i g_{i,t}^{LES} = 0 \tag{3}$$

$$\sum_i \left(q_{i,t}^{LES,in}-q_{i,t}^{LES,out} \right) = 0 \tag{4}$$

$$0 \le g_t^{MEP} \le \overline{G}^{MEP} \tag{5}$$

B. Local Energy Systems' Decision Making Problem

LES are equipped with combined heat and power (CHP) units, auxiliary boiler (AB), heat storage (HS), and electric storage (ES). As it is demonstrated in eq. (2), LES trades energy at equilibrium prices with the MEP and deliver the required services to MED to maximize their profits. The objective function of LESs consist of following terms:

- The incomes from the energy sold (electricity, gas and heat) to MED;
- The costs from trading energy with the MEP in the aggregation equilibrium price. These terms indicate the financial trade between MEP and LESs and are similar in both players objective function. These terms are the coupling variables between MEP and LES

$$
\begin{aligned}
&Max\left\{ g_i(x_i)=\sum_t \Big[\left(P_{i,t}^{MED}\,\Pi_{e,i,t}^{MED} + G_{i,t}^{MED}\,\Pi_{g,i,t}^{MED} + Q_{i,t}^{MED}\,\Pi_{h,i,t}^{MED} \right) \right. \\
&\left. -\left(p_{i,t}^{LES,in}-p_{i,t}^{LES,out} \right)\pi_{e,i,t}^{Agg} - g_{i,t}^{LES}\,\pi_{g,i,t}^{Agg} - \left(q_{i,t}^{LES,in}-q_{i,t}^{LES,out} \right)\pi_{h,i,t}^{Agg} \Big] \right\}
\end{aligned} \tag{6}
$$

The LES operational constraints are modeled based on [9] and [10]. The constraints are LES energy balance, CHP unit constraints, AB Constraints, HS Constraints, and ES Constraints.

LES energy balance: Equations (7)-(9) determine the energy balance for electricity, gas, and heat, respectively.

$$
\begin{aligned}
E_{i,t}^{LES,1} &= P_{i,t}^{MED} - p_{i,t}^{LES,in}\eta_{e,i}^{Trans} + p_{i,t}^{LES,out}/\eta_{e,i}^{Trans} - p_{i,t}^{CHP} \\
&\quad + p_{i,t}^{ES,in} - p_{i,t}^{ES,out} = 0
\end{aligned} \qquad :\lambda_{e,i,t}^{MED} \tag{7}
$$

$$E_{i,t}^{LES,2} = G_{i,t}^{MED} - g_{i,t}^{LES,in} + g_{i,t}^{CHP} + g_{i,t}^{AB} = 0 \qquad :\lambda_{g,i,t}^{MED} \tag{8}$$

$$
\begin{aligned}
E_{i,t}^{LES,3} &= Q_{i,t}^{MED} - q_{i,t}^{LES,in}\eta_{h,i}^{LES} + q_{i,t}^{LES,out}/\eta_{h,i}^{LES} - q_{i,t}^{CHP} \\
&\quad - q_{i,t}^{AB} + q_{i,t}^{HS,in} - q_{i,t}^{HS,out} = 0
\end{aligned} \qquad :\lambda_{h,i,t}^{MED} \tag{9}
$$

Input energy constraints: Input/output energy carriers to/from LES are constrained by their interconnectors' capacities.

$$N_{i,t}^{LES,1}, N_{i,t}^{LES,2} : 0 \le p_{i,t}^{LES,in} \le \overline{P}_i^{LES} \qquad :\underline{\mu}_{e,i,t}^{LES,in}, \overline{\mu}_{e,i,t}^{LES,in} \tag{10}$$

$$N_{i,t}^{LES,3}, N_{i,t}^{LES,4} : 0 \le p_{i,t}^{LES,out} \le \overline{P}_i^{LES} \qquad :\underline{\mu}_{e,i,t}^{LES,out}, \overline{\mu}_{e,i,t}^{LES,out} \tag{11}$$

$$N_{i,t}^{LES,5}, N_{i,t}^{LES,6} : 0 \le q_{i,t}^{LES,in} \le \overline{Q}_i^{LES} \qquad :\underline{\mu}_{h,i,t}^{LES,in}, \overline{\mu}_{h,i,t}^{LES,in} \tag{12}$$

$$N_{i,t}^{LES,7}, N_{i,t}^{LES,8} : 0 \le q_{i,t}^{LES,out} \le \overline{Q}_i^{LES} \qquad :\underline{\mu}_{h,i,t}^{LES,out}, \overline{\mu}_{h,i,t}^{LES,out} \tag{13}$$

$$N_{i,t}^{LES,9}, N_{i,t}^{LES,10} : 0 \le g_{i,t}^{LES} \le \overline{G}_i^{LES} \qquad :\underline{\mu}_{g,i,t}^{LES}, \overline{\mu}_{g,i,t}^{LES} \tag{14}$$

CHP unit constraints: CHP produces electricity and heat by consuming natural gas (15), (16). Furthermore, CHP output heat and electricity should be within its operational limits (17), (18).

$$E_{i,t}^{LES,5} = p_{i,t}^{CHP} - \eta_{e,i}^{CHP} g_{i,t}^{CHP} = 0 \qquad :\lambda_{e,i,t}^{CHP} \tag{15}$$

$$E_{i,t}^{LES,5} = q_{i,t}^{CHP} - \eta_{h,i}^{CHP} g_{i,t}^{CHP} = 0 \qquad :\lambda_{h,i,t}^{CHP} \tag{16}$$

$$N_{i,t}^{LES,11}, N_{i,t}^{LES,12} : 0 \le p_{i,t}^{CHP} \le \overline{P}_i^{CHP} \qquad :\underline{\mu}_{e,i,t}^{CHP}, \overline{\mu}_{e,i,t}^{CHP} \tag{17}$$

$$N_{i,t}^{LES,13}, N_{i,t}^{LES,14} : 0 \le q_{i,t}^{CHP} \le \overline{Q}_i^{CHP} \qquad :\underline{\mu}_{h,i,t}^{CHP}, \overline{\mu}_{h,i,t}^{CHP} \tag{18}$$

AB Constraints: AB produce the required heat by consuming natural gas (19). The output heat of AB should be lower than its maximum capacity (20).

$$E_{i,t}^{LES,7} = q_{i,t}^{AB} - \eta_{h,i}^{AB} g_{i,t}^{AB} = 0 \qquad :\lambda_{h,i,t}^{AB} \tag{19}$$

$$N_{i,t}^{LES,15}, N_{i,t}^{LES,16} : 0 \le q_{i,t}^{AB} \le \overline{Q}_i^{AB} \qquad :\underline{\mu}_{h,i,t}^{AB}, \overline{\mu}_{h,i,t}^{AB} \tag{20}$$

HS Constraints: In (21) it is determined that the heat balance of HS is based on its energy exchange with LES, while (22) and (23) restrict this exchange based on the charge/discharge rates of HS. The stored energy in HS should be lower than the maximum capacity of HS (24). To preserve the energy conservation law in the time horizon, (25) assumes the stored energy in HS to be equal in the first and last time intervals, being half of its maximum capacity.

$$E_{i,t}^{LES,8} = q_{i,t}^{HS} - \left(q_{i,t-1}^{HS}\right)_{t>1} - \left(0.5\overline{Q}_i^{HS}\right)_{t=1} - \eta_{h,i}^{HS,cha} q_{i,t}^{HS,in} + 1/\eta_{h,i}^{HS,dcha}\, q_{i,t}^{HS,out} = 0 \quad : \lambda_{h,i,t}^{HS} \tag{21}$$

$$N_{i,t}^{LES,17}, N_{i,t}^{LES,18} : 0 \le q_{i,t}^{HS,in} \le \gamma_{h,i}^{HS} \quad : \underline{\mu}_{h,i,t}^{HS,in}, \overline{\mu}_{h,i,t}^{HS,in} \tag{22}$$

$$N_{i,t}^{LES,19}, N_{i,t}^{LES,20} : 0 \le q_{i,t}^{HS,out} \le \gamma_{h,i}^{HS} \quad : \underline{\mu}_{h,i,t}^{HS,out}, \overline{\mu}_{h,i,t}^{HS,out} \tag{23}$$

$$N_{i,t}^{LES,21}, N_{i,t}^{LES,22} : 0 \le q_{i,t}^{HS} \le \overline{Q}_{h,i}^{HS} \quad : \underline{\mu}_{h,i,t}^{HS}, \overline{\mu}_{h,i,t}^{HS} \tag{24}$$

$$T_{i,t}^{LES.1}, T_{i,t}^{LES.2} : q_{i,t=1}^{HS} = q_{i,t=T}^{HS} = 0.5\overline{Q}_i^{HS} \quad : \zeta_{h,i,t=1}^{HS}, \zeta_{h,i,t=T}^{HS} \tag{25}$$

ES Constraints: ES constraints are modeled similar to HS. Equations (26)-(30) show the corresponding constraints.

$$E_{i,t}^{LES,9} = p_{i,t}^{ES} - \left(p_{i,t-1}^{ES}\right)_{t>1} - \left(0.5\overline{P}_i^{ES}\right)_{t=1} - \eta_{e,i}^{ES,cha} p_{i,t}^{ES,in} + 1/\eta_{e,i}^{ES,dcha}\, p_{i,t}^{ES,out} = 0 \quad : \lambda_{e,i,t}^{HS} \tag{26}$$

$$N_{i,t}^{LES,23}, N_{i,t}^{LES,24} : 0 \le p_{i,t}^{ES,in} \le \gamma_{e,i}^{ES} \quad : \underline{\mu}_{e,i,t}^{ES,in}, \overline{\mu}_{e,i,t}^{ES,in} \tag{27}$$

$$N_{i,t}^{LES,25}, N_{i,t}^{LES,26} : 0 \le p_{i,t}^{ES,out} \le \gamma_{e,i}^{ES} \quad : \underline{\mu}_{e,i,t}^{ES,out}, \overline{\mu}_{e,i,t}^{ES,out} \tag{28}$$

$$N_{i,t}^{LES,27}, N_{i,t}^{LES,28} : 0 \le p_{i,t}^{ES} \le \overline{P}_{e,i}^{ES} \quad : \underline{\mu}_{e,i,t}^{ES}, \overline{\mu}_{e,i,t}^{ES} \tag{29}$$

$$T_{i,t}^{LES.3}, T_{i,t}^{LES.4} : p_{i,t=1}^{ES} = p_{i,t=T}^{ES} = 0.5\overline{P}_i^{ES} \quad : \zeta_{e,i,t=1}^{ES}, \zeta_{e,i,t=T}^{ES} \tag{30}$$

C. *MPEC formulation of the LES Decision Making Problem*

There is a conflict between MEP and LES decision making. To transform the proposed bi-level problem into a single-level MILP problem, we use Mathematical Programming with Equilibrium Constraints (MPEC) [11] and [12].

The proposed procedure is as follows:

- Transforming the lower-level problem into a convex and linear one;
- Replacing the lower-level problem with its Karush–Kuhn–Tucker (KKT) optimality conditions;
- Applying the strong duality theorem to linearize the non-linear terms of the upper-level problem.

The formulation for LES optimization problem is convex and linear, therefore, (3) shows the Lagrangian of the LES problem and (4)-(7) are its KKT optimality conditions. Equations (4)-(7) are the stationary conditions, the primal optimality conditions and the complementary conditions for the lower-level problem. The linearized form of (7) and the upper-level objective function will be explained in the full paper.

$$\ell_i^{LES} = \mathbf{g}_\mathbf{i}(\mathbf{X}_\mathbf{i}) - \boldsymbol{\mu}_\mathbf{i}^\mathbf{LES}\, \mathbf{N}_\mathbf{i}^\mathbf{LES}(\mathbf{X}_\mathbf{i}) + \boldsymbol{\lambda}_\mathbf{i}^\mathbf{LES}\, \mathbf{E}_\mathbf{i}^\mathbf{LES}(\mathbf{X}_\mathbf{i}) + \boldsymbol{\zeta}_\mathbf{i}^\mathbf{LES} \mathbf{T}_\mathbf{i}^\mathbf{LES}(\mathbf{X}_\mathbf{i}) \tag{31}$$

$$\partial \ell_i^{LES} / \partial \mathbf{X}_\mathbf{i} = 0 \tag{32}$$

$$\partial \ell_i^{LES} / \partial \boldsymbol{\lambda}_\mathbf{i}^\mathbf{LES} = \mathbf{E}_\mathbf{i}^\mathbf{LES}(\mathbf{X}_\mathbf{i}) = 0 \tag{33}$$

$$\partial \ell_i^{LES} / \partial \boldsymbol{\zeta}_\mathbf{i}^\mathbf{LES} = \mathbf{T}_\mathbf{i}^\mathbf{LES}(\mathbf{X}_\mathbf{i}) = 0 \tag{34}$$

$$\mathbf{0} \le \boldsymbol{\mu}_\mathbf{i}^\mathbf{LES} \perp \mathbf{N}_\mathbf{i}^\mathbf{LES}(\mathbf{X}_\mathbf{i}) \ge \mathbf{0} \tag{35}$$

IV. MATHEMATICAL FORMULATION OF THE ELECTRICITY MARKET

The MEP is a strategic player that competes with other players in an electricity wholesale market. This behavior is modeled using bi-level optimization, where the MEP resolves its strategy in the upper level and the impact of its decision on electricity market parameters is determined in the lower level. In the lower level, the ISO receives the market players bids/offers and clears the market to maximize social welfare (8). The first two terms of this equation are the offers and bids of the MEP as a simultaneous electricity producer and consumer. The next two terms are the other electricity market players' strategies that consist of the Gencos' offers and the retailers bids.

$$Max \left\{ h(x) = \sum_t \left[\pi_t^{MEP,Offer} p_t^{MEP,out} - \pi_t^{MEP,Bid} p_t^{MEP,in} + \sum_k \Pi_{k,t}^{Genco,Offer} p_{k,t}^{Genco} - \sum_j \Pi_{j,t}^{Retailer,Bid} p_{j,t}^{Retailer} \right] \right\} \tag{36}$$

The power balance of the electricity market is shown in (9). The dual variable of this equation is the market clearing price. In addition, (10)-(13) show the upper limits of generation/demand, which are equal to the offers/bids.

$$E_t^{EM,1} : \sum_k p_{k,t}^{Genco} - \sum_j p_{j,t}^{Retailer} + p_t^{MEP,out} - p_t^{MEP,in} = 0 \quad \kappa_t^{EM} \tag{37}$$

$$N_{k,t}^{EM,1}, N_{k,t}^{EM,2} : 0 \le p_{k,t}^{Genco} \le \overline{P}_k^{Genco} \quad : \underline{\mu}_{k,t}^{GenCo}, \overline{\mu}_{k,t}^{GenCo} \tag{38}$$

$$N_{j,t}^{EM,3}, N_{j,t}^{EM,4} : 0 \le p_{j,t}^{Retailer} \le \overline{P}_j^{Retailer} \quad : \underline{\mu}_{j,t}^{RetailCo}, \overline{\mu}_{j,t}^{RetailCo} \tag{39}$$

$$N_t^{EM,5}, N_t^{EM,6} : 0 \le p_t^{MEP,in} \le \overline{P}^{MEP} \quad \underline{\mu}_t^{MEP,in}, \overline{\mu}_t^{MEP,in} \tag{40}$$

$$N_{i,t}^{EM,7}, N_{i,t}^{EM,8} : 0 \le p_t^{MEP,out} \le \overline{P}^{MEP} \quad \underline{\mu}_t^{MEP,out}, \overline{\mu}_t^{MEP,out} \tag{41}$$

Equations (8)-(13) represent another lower-level problem of the MEP, in this case related to the electricity market behavior. The procedure for converting this bi-level problem is the same as the one in Section III.C. After transforming the electricity market level, the three- level optimization problem is converted into a single-level MILP problem whose objective function is given in (1) after linearizing the non-linear terms, with the set of LES and energy markets constraints.

V. NUMERICAL RESULTS

In the numerical results the behavior of MEP to interact with LES and its participation in wholesale electricity market is investigated. The model have been solved by CPLEX 10 on HP Z800 workstation with CPU: 3.47 GHz and RAM: 96 GB.

The MEP aggregates three LESs inside and competes with 10 Gencos and 10 retailers in the electricity market. Fig. 2 shows the energy carrier prices for the LES and electricity market clearing prices. As shown, due to the small energy exchange of the MEP, this player is a price taker in the electricity market and the market price is solely determined based on Gencos' and retailers' offers and bids, respectively. *1) Natural gas:* Natural gas is a grid-bounded carrier that cannot be produced locally and the MEP delivers the required amount to LESs. Thus, its price always equals the price cap and the MEP maximizes its profit by maximizing the gas price.

2) Heat: Heat is a local energy carrier and is produced only by AB and CHP units. Therefore, its price depends on local operational considerations. In hours 2-13, while the heat production of CHP units does not satisfy MED needs and the LES use their AB (CHP units are in heat-lead mode), the heat price is equal to the marginal cost of the AB. On the other hand, after hour 13, while the price of electricity is high and the CHP units are in electricity-lead mode, the price of heat is almost equal to zero and heat will be produced as a supplementary good when generating electricity in the CHP units. As a matter of fact, producing heat is like a bonus for LESs helping them to operate their CHP units within their operational limits.

3) Electricity: Electricity can be generated locally and delivered by the macro-MES. The electricity price has the same behavior as the electricity market price.

Fig. 3 depicts the impact of increasing the share of MEP on the electricity market. In this paper, this share is defined as the share of the MEP electricity demand with respect to the total demand of the system. As shown, by increasing the share of MEP, electricity prices will increase in most periods (hours 1-10 and 13-19). However, in hour 11, with a market share of more than 35%, electricity prices will decrease. In this hour, the MEP injects its electricity surplus to the grid.

Figs. 4 and 5 depict the electricity and heat equilibrium prices for the aggregation of LES for various market share of MEP, respectively. By increasing the electricity market price, the equilibrium electricity price increases and it motivates LES to use their internal resources (CHP units and ES) to generate electricity locally. Therefore, the price of heat as a supplementary production in the CHP process decreases in the corresponding hours. It should be noted that in some hours due to high price of electricity the heat CHP production will be profitable even with minimum price which is approximately equal to zero.

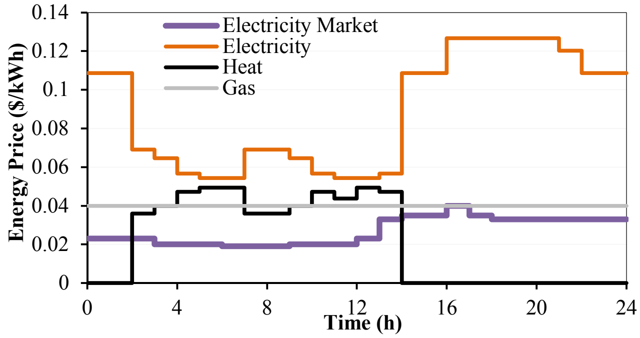

Fig. 2. Energy carrier prices for aggregated LESs and clearing prices of the electricity market.

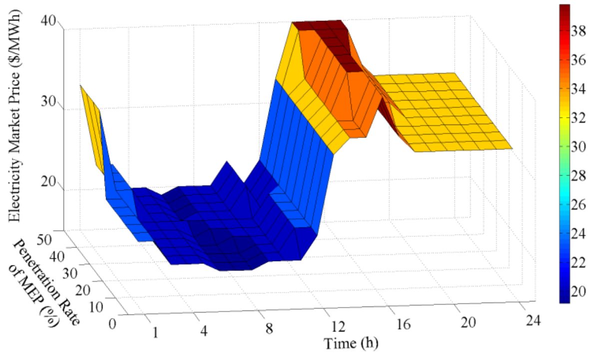

Fig. 3. Impact of increasing the share of MEP on market prices.

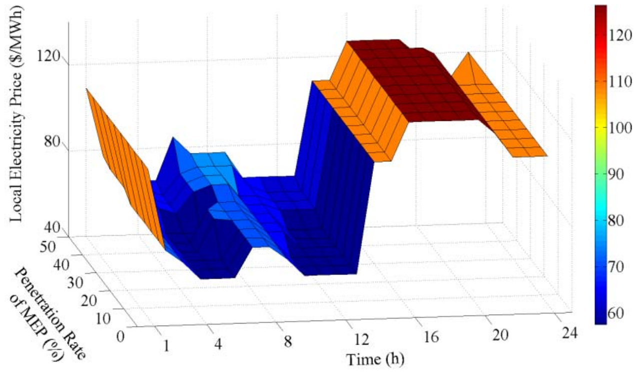

Fig. 4. Impact of increasing the market share of MEP on aggregator's electricity price.

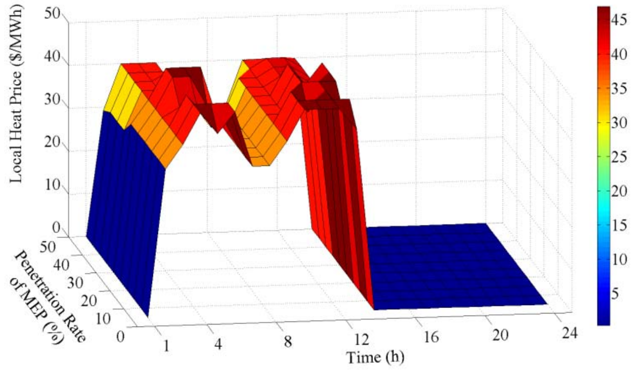

Fig. 5. Impact of increasing the market share of MEP on aggregator's heat price.

Note that, in general, MEP expansion maintains the adequacy of generation by using local energy resources, but these resources are also correlated to the local operational considerations. For instance, the electricity production of CHP units and its marginal cost is related to the heat consumption of the MED. Although in case of a contingency these local resources can protect the system and increase reliability indices, in a normal operation the local constraints determine their capability to rival with the other market players. Therefore, in comparison with bulk generation, these resources are not beneficial at all times.

Moreover, their marginal costs are not only related to their levels of production but also dependent on their local operational considerations, being different in various time intervals. In the case studied, the lowest marginal cost for CHP production is during hours 11-13, while the MEP has the maximum heat consumption, but the system peak occurs between hours 14-17.

VI. CONCLUSION

In this paper, the behavior of an MEP was investigated for a simultaneous behavior to aggregate a set of LES and participate in the wholesale electricity markets. Moreover, the impacts of increasing the market share of MEP on these two sets of equilibrium prices were studied. Numerical results showed that local energy price equilibrium was related to the local energy resources of LESs. Due to the mutual dependency of the energy carriers, LES may have variable marginal costs for the energy production in the operation period. This time-based marginal cost affected local market parameters and, if the market share of MEP increases, it can affect them. Although the changes in the electricity market price may be small, they affected the strategy of the other electricity market players. MEP increased the total efficiency of the system, but it does not mean that they can decrease the price or the demand in the peak hour. The energy produced by the MEP was more related to local operational considerations, rather than the electricity market price.

ACKNOWLEDGMENTS

This work was supported by FEDER funds through COMPETE 2020 and by Portuguese funds through FCT, under Projects SAICT-PAC/0004/2015 - POCI-01-0145-FEDER-016434, POCI-01-0145-FEDER-006961, UID/EEA/50014/2013, UID/CEC/50021/2013, and UID/EMS/00151/2013. Also, the research leading to these results has received funding from the EU Seventh Framework Programme FP7/2007-2013 under grant agreement no. 309048. Moreover, N. Neyestani acknowledges funding from Project SusCity - MITPTB/CS/0026/2013.

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