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Modeling the Impact of Multi-Energy Players on Electricity Market in Smart Grid Environment

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***Abstract*— Future energy system is highly integrated system from both energy carriers and decision making points of view. In such a system, a multi energy player (MEP) is defined as an energy player who can convert and store a set of energy carriers. These players consist of local energy resources and behave as both consumer and producer in individual energy markets. As a matter of fact, MEPs are links among energy markets and enhance total flexibility of multi-energy system (MES). With increasing the share of MEPs in electricity market, their operational flexibility can affect market variables. In this paper, at first the behavior of a typical MEP is modeled in electricity market. After that the share of MEP in electricity market is increased to survey its impact on electricity market interactions. Moreover, the impact of MEP's gas contract on its behavior in electricity market is investigated. The numerical results illustrate the impact of these factors on electricity market parameters.**

Keywords*— Mathematical programing with equilibrium constraints (MPEC), multi-energy player (MEP), multi-energy system (MES), strategic behavior.

I. NOMENCLATURE

Subscripts

e	Electricity
g	Natural gas
h	Heat
i	i'th LES
j	j'th Genco.
k	k'th Retailer
t	Time interval

Superscripts

AB	Auxiliary boiler
Bid	Bidding of energy consumers
CHP	Combined heat and power
Forecast	Forecasted amount of RERs
Genco	Generation company (Genco).
IL	Interruptible load
in	Input energy to MEP or LES
inj	Injected energy of MEP and LES to electricity market
LES	Local multi-energy system
MED	Multi-energy demand
MEP	Multi-energy player
Offer	Offering of energy producers
PV	Photo-voltaic
Retailer	Retailer
Wind	Wind generation

Parameters and Variables

C	Cost of load interruption
g, G	Natural gas
p, P	Electricity
q, Q	Heat
λ	Dual variable for equality constraints
$\underline{\mu}, \overline{\mu}$	Dual variable for lower and upper limits in non-equality constraints
η	Efficiency
φ	Heat to electricity ratio
π, Π	Energy price

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

II. INTRODUCTION

A. Motivation and Aim

Introducing new energy facilities (e.g. energy converters and storages) and restructuring in energy sector increase the dependency and conflict among energy players. The concept of multi-energy system (MES) is developed to confront these issues from both technical and economical points of view [1]. MES is integration of various energy carriers (e.g. electricity and natural gas) that facilitates energy and information interaction among multi-energy players (MEP). On the contrary of conventional energy players, MEPs can receive and serve more than one energy carriers and equipped by energy converters and storages for altering energy pattern based on coupling signals (i.e. energy price) [2].

Flexibility of MEPs to change their energy pattern among energy carriers and time intervals motivates decision makers to implement this opportunity in MES management [3]. Therefore, by increasing the level of competitiveness in the system, decision makers try to enhance the participation share of MEPs in system interactions. Modeling the impact of MEPs in individual energy carriers market (i.e. electricity market in this paper) and investigating the future power system parameters with increasing the share of these players is one of the main topics.

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B. Literature review and Contributions

The MES is explained as a system with more than one energy carrier [1]. Energy hub system and matrix modeling are two approaches that model the cross impact of energy carriers in MES and consists of both physical and decision making characteristics of MES [4] and [5]. These models are developed and new energy elements (e.g. energy converters, storages, local resources, and etc.) are modeled in them. Reference [6] has modeled energy storage in energy hub approach and renewable energy resources are modeled in [7]. Moreover demand side management and demand response (DR) are integrated in these models and energy hub is proposed as source of DR programs [8] and [9]. Plug-in electric vehicles (PEV) as future transportation system have modeled in energy hub approach and the impacts of these facilities on power system have investigated [2].

The energy flow calculations are represented in [10] and the new heuristic technique has proposed in [11] to solve this large scale and complex problem. Moreover for modeling the cooperation environment of energy hubs in a MES, reference [12] architectures a decentralized control system based on the hubs' energy interactions and marginal cost of energy production. In this paper the impact of a MEP is investigated in electricity market parameters. For this purpose, a bi-level modeling approach is considered to model the behavior of MEP and electricity market in two levels. The model is transformed to a single level problem by applying duality theorem.

C. paper organization

The remaining sections of this paper are as follow:

In Section 2 the short description of problem structure is presented. Sections 3 and 4 are represented MEPs and electricity market mathematical model, respectively. Moreover, the numerical results are illustrated in Section 5 and concluding remarks are denoted in Section 6.

III. PROBLEM DESCRIPTION

In this paper, the strategic behavior of a MEP is modeled and investigated in electricity market. The MEP aggregates a set of local multi-energy systems (LES). The LESs are equipped by combined heat and power (CHP) unit, auxiliary boiler (AB), interruptible load (IL), and renewable energy resources (RERs), which deliver required energy services to the multi-energy demands (MEDs). The RERs in this paper are wind turbines and photo-voltaic arrays that their output power is forecasted for operation time horizon.

As it is shown in fig. 1 the strategic behavior of MEP on electricity market price is modeled through a bi-level problem. In the upper level problem, the MEP maximizes its profit by trading energy with electricity market while deliver required energy carriers to the MEDs of LESs. The output of this level is the quantity and price of energy that MEP should trade with the electricity market. The main point of this level is the double role of MEP as producer and consumer in electricity market, which is highly dependent with the equilibrium price of energy market.

In the lower level problem, there is a pool-based electricity market that the independent system operator (ISO) clears the market price and maximizes the social welfare to determine the share of each player in market energy balance. In this paper, the market players are considered as Gencos and retailers who announce their electricity offers/bids to the ISO for time horizon of operation problem in advance and in single price-quantity step. The output of this level is the electricity market clearing price that affects the strategy of MEP in electricity market.

This bi-level problem is transformed to a single level mixed-integer linear programming (MILP) by applying dual theorem. Therefore, the lower level problem (electricity market level) is replaced by its KKT optimality conditions and then the non-linear terms of objective function are linearized using strong duality theorem.

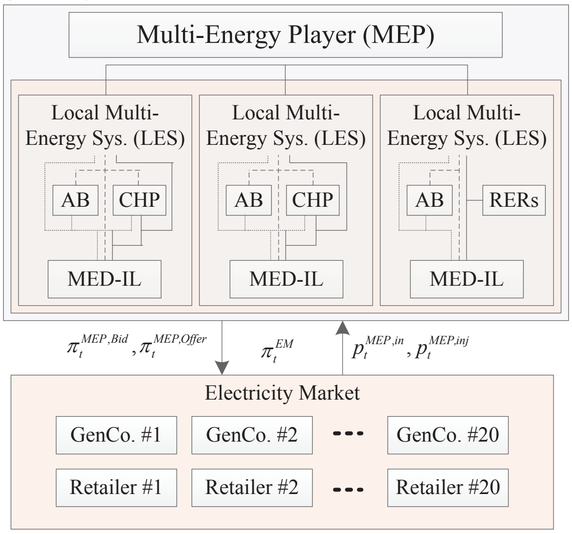

Fig. 1. A schematic of the strategic behavior of MEP in electricity market.

IV. MATHEMATICAL MODELING

A. Bi-Level Formulation

The proposed bi-level model is described by (1)-(28). Equation (1) demonstrates the objective function of MEP including MEP's profit from trading energy with electricity market, its cost from buying natural gas, and interrupting the electricity demand, respectively. Moreover, (2)-(6) shows the restriction of energy trade for MEP with electricity market and LESs due to interconnectors limitation. Each LES interacts electricity, gas, and heat with MEP to deliver required energy services. Equations (7)-(9) demonstrate energy balance for electricity, gas, and heat in each LES, respectively. The loss in the district heating system among MEP is modeled by η_i^{Pipe} in equation (9). In addition, the amount of energy interactions among the LESs are restricted by the interconnectors' capability, which are represented by equations (10)-(12). CHP unit and AB are considered as two types of energy converters for LES. CHP unit converts input natural gas to the output electricity and heat (equations (13) and (14)). The output heat and electricity should be in their operational bounds (equations (15) and (16)) and their ratio should be constant (equation (17)). Moreover, AB converts input natural gas to the output

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heat energy. Similar to CHP unit, AB's heat output should respect its operational limit (equations (18) and (19)). Equations (20) and (21) demonstrate the forecasted output power of wind and PV.

$$Maximize\left\{\left\{-(p_t^{MEP,in}-p_t^{MEP,inj})\pi_t^{EM}-g_t^{MEP}\Pi_{g,t}^{GM}-\sum_i C_{i,t}^{IL}p_{i,t}^{IL}\right\}\right. \quad (1)$$

$Subject\ to$:

$$p_t^{MEP,in}-p_t^{MEP,inj}-\sum_i(p_{i,t}^{LES,in}-p_{i,t}^{LES,inj})=0 \quad (2)$$

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

$$\sum_i(q_{i,t}^{LES,in}-q_{i,t}^{LES,inj})=0 \quad (4)$$

$$0\le p_t^{MEP,in},p_t^{MEP,inj}\le \overline{P}^{Ma} \quad (5)$$

$$0\le g_t^{MEP}\le \overline{G}^{Ma} \quad (6)$$

$$P_{i,t}^{MED}-p_{i,t}^{LES,in}\eta_i^{Trans}+\frac{p_{i,t}^{LES,inj}}{\eta_i^{Trans}}-p_{i,t}^{CHP}-p_{i,t}^{PV}-p_{i,t}^{Wind}-p_{i,t}^{IL}=0 \quad (7)$$

$$G_{i,t}^{MED}-g_{i,t}^{LES}+g_{i,t}^{CHP}+g_{i,t}^{AB}=0 \quad (8)$$

$$Q_{i,t}^{MED}-q_{i,t}^{LES,in}\eta_i^{Pipe}+\frac{q_{i,t}^{LES,inj}}{\eta_i^{Pipe}}-q_{i,t}^{CHP}-q_{i,t}^{AB}=0 \quad (9)$$

$$0\le p_{i,t}^{LES,in},p_{i,t}^{LES,inj}\le \overline{P}_i^{LES} \quad (10)$$

$$0\le g_{i,t}^{LES,in}\le \overline{G}_i^{LES} \quad (11)$$

$$0\le q_{i,t}^{LES,in},q_{i,t}^{LES,inj}\le \overline{Q}_i^{LES} \quad (12)$$

$$p_{i,t}^{CHP}=\eta_{e,i}^{CHP}g_{i,t}^{CHP} \quad (13)$$

$$q_{i,t}^{CHP}=\eta_{h,i}^{CHP}g_{i,t}^{CHP} \quad (14)$$

$$\underline{P}_i^{CHP}\le p_{i,t}^{CHP}\le \overline{P}_i^{CHP} \quad (15)$$

$$\underline{Q}_i^{CHP}\le q_{i,t}^{CHP}\le \overline{Q}_i^{CHP} \quad (16)$$

$$\varphi_i^{CHP}=q_{i,t}^{CHP}\big/p_{i,t}^{CHP} \quad (17)$$

$$q_{i,t}^{AB}=\eta_{h,i}^{AB}g_{i,t}^{AB} \quad (18)$$

$$0\le q_{i,t}^{AB}\le \overline{Q}_i^{AB} \quad (19)$$

$$0\le p_{i,t}^{Wind}\le P_{i,t}^{Wind,Forecast} \quad (20)$$

$$0\le p_{i,t}^{PV}\le P_{i,t}^{PV,Forecast} \quad (21)$$

$$0\le p_{i,t}^{IL}\le \alpha_i P_{i,t}^{MED} \quad (22)$$

$$Where\ \mathbf{\Gamma_t}\in arg\left\{Minimize-\left(\sum_j\Pi_{j,t}^{Retailer,Offer}p_{j,t}^{Retailer}\right.\right.$$
$$\left.-\sum_k\Pi_{k,t}^{GenCo.,Offer}p_{k,t}^{GenCo.}+\pi_t^{MEP,Bid}p_t^{MEP,in}-\pi_t^{MEP,Offer}p_t^{MEP,inj}\right) \quad (23)$$

$$\sum_k p_{k,t}^{GenCo.}-\sum_j p_{j,t}^{Retailer}+p_t^{MEP,inj}-p_t^{MEP,in}=0 \quad :\lambda_t \quad (24)$$

$$0\le p_{k,t}^{GenCo.}\le \overline{P}_k^{GenCo.} \quad :\underline{\mu}_{k,t}^{GenCo.},\overline{\mu}_{k,t}^{GenCo.} \quad (25)$$

$$0\le p_{j,t}^{Retailer}\le \overline{P}_j^{Retailer} \quad :\underline{\mu}_{j,t}^{Retailer},\overline{\mu}_{j,t}^{Retailer} \quad (26)$$

$$0\le p_t^{MEP,in}\le \overline{P}^{MEP} \quad :\underline{\mu}_t^{MEP,in},\overline{\mu}_t^{MEP,in} \quad (27)$$

$$0\le p_t^{Ma,inj}\le \overline{P}^{Ma} \quad :\underline{\mu}_t^{MEP,inj},\overline{\mu}_t^{MEP,inj}\Big\},\forall t \quad (28)$$

In this paper, ISO is the operator of a day-ahead electricity market and Gencos, retailers, and a MEP are considered as market players. The ISO receives bids and offers for 24 hours in advance and clears the electricity price to maximize the social welfare of the players in each time interval. Equation (23) demonstrates the objective function of ISO to maximize the social welfare. The objective function terms are the bids of retailers, the offers of Gencos, the bid of MEP, and the offer of MEP in each hour, respectively. Moreover, ISO should control energy balance in each hour (equation (24)) while considering maximum bidding and offering of each player (equations (25)-(28)). The variables in the right side of the equation (24)-(28) are dual variables for each equation that will be used to transform lower level problem to its dual problem

B. *Mathematical Programming with Equilibrium Constraints (MPEC)*

The following procedure should be considered for transforming the bi-level optimization problem to a single-level MILP problem that can be solved by conventional MILP solvers [13].

- Considering decision variables of upper level problem ($p_t^{MEP,in}$, $p_t^{MEP,inj}$) as input parameter of lower level problem;
- Replacing lower level problem by its KKT optimality conditions;
- Implementing strong duality theorem to linearize non-linear terms of upper level problem ($p_t^{MEP,in}\pi_t^{EM}$, $p_t^{MEP,inj}\pi_t^{EM}$).

In this regard, (29)-(41) demonstrate the transformed version of bi-level problem to a single level MILP problem. Equation (29) is the objective function of MEP that is linearized by implementing strong duality that is presented in Section IV.C. Moreover, (2)-(22) and (24) that are upper level constraints and lower level equality constraint are used directly. Equations (30)-(33) show stationarity conditions that are the first derivation of lower level problems decision variables including $p_{j,t}^{Retailer}$, $p_{k,t}^{GenCo.}$, $p_t^{MEP,in}$, $p_t^{MEP,inj}$. In addition, the complementary conditions for non-equality equations of lower level problem are represented by (34)-(41).

$$Maximize\left\{g_t^{MEP}\Pi_{g,t}^{GM}+\sum_i C_{i,t}^{IL}p_{i,t}^{IL}+\sum_k\overline{\mu}_{k,t}^{GenCo.}\overline{P}_k^{GenCo.}+\right.$$
$$\left.\sum_j\overline{\mu}_{j,t}^{Retailer}\overline{P}_j^{Retailer}-\sum_j\Pi_{j,t}^{Retailer,Bid}p_{j,t}^{Retailer}+\sum_k\Pi_{k,t}^{GenCo.,Offer}p_{k,t}^{GenCo.}\right\} \quad (29)$$

$Subject\ to$:

Equations (2)-(22).

Equation (24).

$$-\Pi_{j,t}^{Retailer,Bid}+\lambda_t-\underline{\mu}_{j,t}^{Retailer}+\overline{\mu}_{j,t}^{Retailer}=0 \quad (30)$$

$$\Pi_{k,t}^{GenCo.,Offer}-\lambda_t-\underline{\mu}_{k,t}^{GenCo.}+\overline{\mu}_{k,t}^{GenCo.}=0 \quad (31)$$

$$-\pi_t^{MEP,Bid}+\lambda_t-\underline{\mu}_t^{MEP,in}+\overline{\mu}_t^{MEP,in}=0 \quad (32)$$

$$\pi_t^{MEP,Offer}-\lambda_t-\underline{\mu}_t^{MEP,inj}+\overline{\mu}_t^{MEP,inj}=0 \quad (33)$$

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$$0 \le \underline{\mu}_{k,t}^{GenCo.} \perp p_{k,t}^{GenCo.} \ge 0 \tag{34}$$

$$0 \le \overline{\mu}_{k,t}^{GenCo.} \perp \left(\overline{P}_{k}^{GenCo.} - p_{k,t}^{GenCo.} \right) \ge 0 \tag{35}$$

$$0 \le \underline{\mu}_{j,t}^{Retailer} \perp p_{j,t}^{Retailer} \ge 0 \tag{36}$$

$$0 \le \overline{\mu}_{j,t}^{Retailer} \perp \left(\overline{P}_{j}^{Retailer} - p_{j,t}^{Retailer} \right) \ge 0 \tag{37}$$

$$0 \le \underline{\mu}_{t}^{MEP,in} \perp p_{t}^{MEP,in} \ge 0 \tag{38}$$

$$0 \le \overline{\mu}_{t}^{MEP,in} \perp \left(\overline{P}^{MEP} - p_{t}^{MEP,in} \right) \ge 0 \tag{39}$$

$$0 \le \underline{\mu}_{t}^{MEP,inj} \perp p_{t}^{MEP,inj} \ge 0 \tag{40}$$

$$0 \le \overline{\mu}_{t}^{MEP,inj} \perp \left(\overline{P}^{MEP} - p_{t}^{MEP,inj} \right) \ge 0 \tag{41}$$

C. *Strong Duality*

In order to linearize the objective function, strong duality theory is implemented. The strong duality condition states that the gap between the primal and dual optimal values is approximately zero at optimality and the primal and dual objective functions can be equal.

For wholesale electricity market, equation (42) shows the strong duality condition for linearizing $p_t^{MEP,in}\pi_t^{MEP,Bid}$ and $p_t^{MEP,inj}\pi_t^{MEP,Offer}$ in the MEP objective function.

$$\begin{aligned} & -\left[\begin{aligned} & \sum_j \Pi_{j,t}^{Retailer,Bid} p_{j,t}^{Retailer} - \sum_k \Pi_{k,t}^{Genco,Offer} p_{k,t}^{Genco} \\ & + \Pi_t^{MEP,Bid} p_t^{MEP,in} - \Pi_t^{MEP,Offer} p_t^{MEP,inj} \end{aligned} \right] \\ & = -\sum_j \overline{\mu}_{j,t}^{Retailer} \overline{p}_j^{Retailer} - \sum_k \overline{\mu}_{k,t}^{Genco} \overline{p}_k^{Genco} \\ & - \overline{\mu}_t^{MEP,in} \overline{p}^{MEP} - \overline{\mu}_t^{MEP,inj} \overline{p}^{MEP} \end{aligned} \tag{42}$$

Equations (32) and (33) determine the stationary conditions for $p_t^{MEP,in}$ and $p_t^{MEP,inj}$, respectively. From these equations we can calculate the amount of $\pi_t^{MEP,Offer}$ and $\pi_t^{MEP,Bid}$ in (42).

By substituting these relations using (42), the linear form of $p_t^{MEP,in}\kappa_t^{EM}$ and $p_t^{MEP,out}\kappa_t^{EM}$ will be as in (43).

$$\begin{aligned} & \left[-\lambda_t p_t^{MEP,in} + \lambda_t p_t^{MEP,inj} \right] = \\ & -\sum_j \overline{\mu}_{j,t}^{Retailer} \overline{p}_j^{Retailer} - \sum_k \overline{\mu}_{k,t}^{Genco} \overline{p}_k^{Genco} \\ & + \sum_j \Pi_{j,t}^{Retailer,Bid} p_{j,t}^{Retailer} - \sum_k \Pi_{k,t}^{Genco,Offer} p_{k,t}^{Genco} \end{aligned} \tag{43}$$

TABLE I
DATA OF LOCAL ENERGY RESOURCES

	CHP #1	CHP #2	AB #1	AB #2	AB #3
Output Electricity	2.5 MW	1.5 MW	---	---	---
Output Heat	3 MW	2.2 MW	2 MW	3 MW	1.5 MW
η_e	0.43	0.45	---	---	---
η_h	0.35	0.3	0.9	0.85	0.9

V. NUMERICAL RESULTS

In this paper, the MEP aggregates a set of LESs that are equipped by local energy resources. Table I shows the local energy resources that are utilized in these LESs. Each LES has a main transformer ($\eta_i^{Trans} = 0.95$) to connect to the upstream network. Due to high energy loss for district heating system, the efficiency of heat interconnectors is assumed as 0.9. Furthermore, 5% of electrical demand in each LES is considered as IL ($\alpha_i = 0.05$). Based on the integration of these elements in LESs, three types of LESs are considered in this section as follow:

- Type #1: including CHP #1, AB #1, and IL #1;
- Type #2: including CHP #2, AB #2, and IL #2;
- Type #3: including AB #3, PV, Wind, and IL #3.

To evaluate the behavior of MEP in electricity market three cases are considered as follow:

Case I: In this case, MEP is a price taker player in electricity market. Figure 2 depicts gas and electricity prices in wholesale gas and electricity markets, respectively. In this case it is assumed that MEP consists three LESs based on three types of LES. Due to small scale of MEP, it has no impact on electricity market equilibrium and is considered as price taker player. The equilibrium price is based on the interaction of other market players (Gencos and retailers). As it is shown in fig.3 and fig.4 each local energy resource produces electricity and heat energy based on local operational restrictions and upstream energy prices. Wind and PV are renewable energy resources and their generation cost is assumed as zero; therefore, they generate electricity in their maximum capacity based on the forecasted amounts. Moreover, after hour 6 while the electricity price has been increased, the CHP units generate electricity and heat simultaneously. It should be noted that the amount of CHP generation is related to the local heat consumption that determines the profitability of CHP production. Moreover, due to more efficiency of CHP #1, it has more share of generation in hours 7-24 rather than CHP #2.

On the other hand, in hours 9-12 and 18-20 while the electricity price is high and the LES has high amount of local heat consumption, the MEP injects its surplus energy to the upstream network. In hours 11-13 both the energy price and renewable generation are high therefore, LES Type #3 (renewable based) has surplus generation while LESs type #1 and type #2 haven't enough electricity generation and use their IL capability to reduce their operation cost.

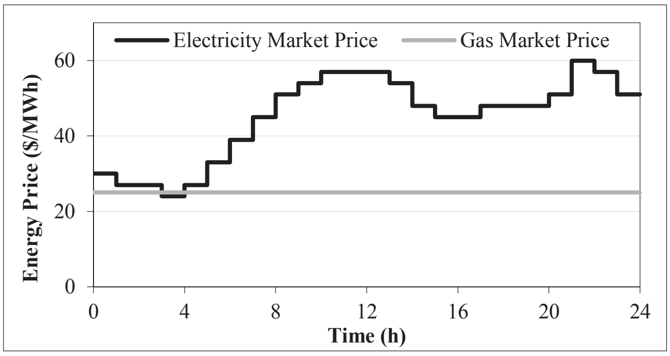

Fig. 2. Gas and electricity prices in their markets while MEP is a price taker player.

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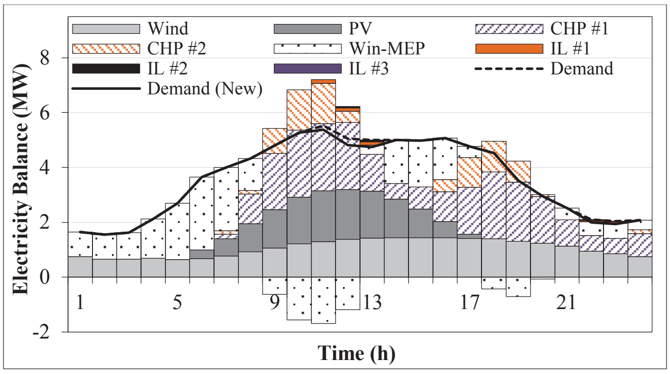

Fig. 3. Share of each local energy resource in electricity balance of MEP.

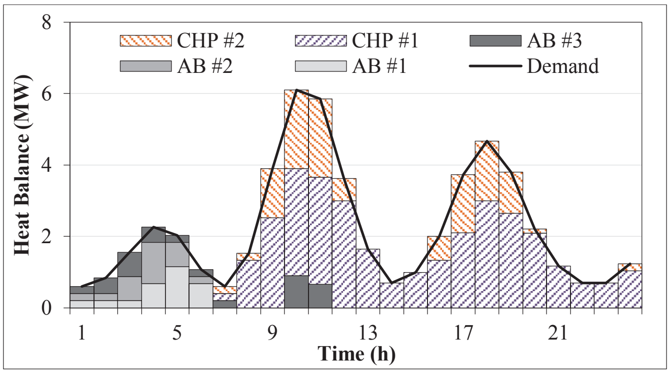

Fig. 4. Share of each local energy resource in heat balance of MEP.

Case II: In this case the number of LESs for MEP is increased gradually and its impact on MEP behavior in electricity market is evaluated. By increasing the number of LESs, the market share of MEP in electricity market increases and consequently, enhances MEP's capability to impact on the electricity market equilibrium. On the contrary, the change in the equilibrium price will impact on the strategy of MEP to utilize its local energy resources. As shown in fig. 5, by increasing the number of LESs, in the first peak period (9-13) the electricity price has decreased while in the valley (3-6) the electricity price has increased. In fact, by increasing the number of LESs, the electricity price profile will be smoother. The higher heat consumption lead to more utilization of CHP units and lower marginal cost of electricity production for MEP that impact directly on the electricity price in first peak period.

Case III: In this case the gas price for MEP is increased and its impact on MEP behavior in electricity market is investigated. As shown in fig. 6 by increasing the gas price, the equilibrium price will increase in electricity market. The main energy resources in LESs are CHP units and RERs. RERs generate electricity based on their primary energy resources characteristics and CHP units production depends on the local heat consumption and gas price. Therefore, in this case by increasing the gas price the marginal cost of energy production in CHP units will increase. On the other hand, Due to double role of MEP as a prosumer in electricity market, it plays the role of marginal unit in most of the hours and increasing the price of its gas supply contract can directly mitigate its capability to compete in market and increase the market equilibrium point.

VI. CONCLUSION

In this paper the behavior of MEP in a competitive electricity market have been investigated. In this regard, a bi-level optimization approach is implemented that in its upper level problem, a MEP and its interior LESs have been modeled and in the lower level problem is electricity market including Gencos and retailers. The bi-level problem has been transformed to a MILP single level problem by implementing duality theorem. The numerical results show the behavior of a single MEP in electricity market as a price taker player. Moreover, complementary case studies confirm the role of integrated modeling for MES in demand side that facilitates the implementation of all resources efficiently and increasing the operational flexibility of LESs. The dual behavior of MEPs as producer and consumers brings flexibility to whole system to fill market demand valleys by MEPs consumption and shave its peak with MEPs generation. This impact makes a smother load pattern for whole system and increases system total efficiency.

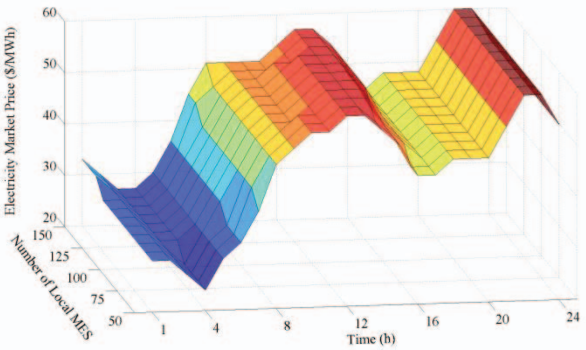

Fig. 5. The impact of increasing the number of LESs on electricity market equilibrium.

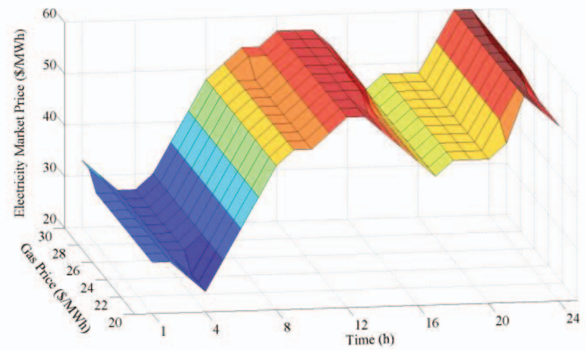

Fig. 6. The impact of increasing the gas price on electricity market equilibrium.

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