Bi-Level Approach for Modeling Multi-Energy Players' Behavior in a Multi-Energy System

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***Abstract*—In this paper a bi-level approach is presented to model the behavior of multi-energy players (MEP) who are coupled based on signal price in a multi-energy system (MES). The MEPs are defined as energy players who can trade more than one energy carrier and have energy facilities (e.g. energy storages and converters) to convert and store various energy carriers. In this approach, MEPs trade various energy carriers in the upper level problem and the coupled energy price will be deduced. In the lower level problem MEPs schedule their energy balance based on the upper level signal price. By implementing dual theorem, the bi-level problem is transformed into a single level optimization problem that can be solved with CPLEX optimizer. The proposed model has been applied in an MES with four MEPs and the numerical results demonstrate the proficiency of the modeling framework.**

***Index Terms*—Equilibrium constraints, multi-energy players, multi-energy system, energy market.**

I. Nomenclature

Subscripts

e, g, h	Electricity, natural gas, and heat respectively.
i	Micro-MES
t	Time interval

Superscripts

AB	Auxiliary boiler
CHP	Combined heat and power
in	Input energy to Micro-MES
inj	Injected energy to Macro-MES
Ma	Macro-MES
Mi	Micro-MES
MED	Multi-energy demand
$Ratio$	Heat to electricity ratio of CHP unit

Parameters and Variables

g, G	Natural gas
q, Q	Heat
w, W	Electricity
λ	Dual variable for equality constraints
$\underline{\mu}, \overline{\mu}$	Dual variable for lower and upper limits in non-equality constraints
φ	Heat to electricity ratio of CHP unit
η	Efficiency
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 the 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. MES is integration of various energy carriers (e.g. electricity and natural gas) that facilitates energy and information interaction between multi-energy players (MEP) [1]. On the contrary to conventional energy players, MEPs can receive and serve more than one energy carrier and equipped by energy converters and storages for altering energy patterns based on coupling signals (i.e. energy price).

Flexibility of MEPs to change their energy pattern between energy carriers and time intervals motivates decision makers to implement this opportunity in MES management. Therefore, by increasing the level of competitiveness in the system, decision makers try to enhance the participation share of MEPs in system interactions. Modeling this multi-administrative system that considers the role of each MEP is the main aim of this paper.

B. Problem Description

In this paper, MES consists of four layers namely multi-energy demand (MED), micro-MES, macro-MES, and energy market. Fig. 1 demonstrates the energy interaction between these layers and the short description of each layer is as follow:

- MED: MED can be considered as integration of smart buildings or industrial plants that can change their energy consumption patterns during the day through small scale energy converters (e.g. micro-combined heat and power (CHP) units) and storages (e.g. heat storage and plug-in electric vehicles (PHEVs)).

- Micro-MES: micro-MES is a local energy network that is equipped by medium scale energy resources and serves various energy carriers to MEDs.
- Macro-MES: Macro-MES are integration of a set of micro-MESs and consists of some bulk energy resources. They trade energy with micro-MESs in local energy market and other macro-MESs in wholesale energy market.
- Energy Market: energy market is a main competition environment in proposed fractal structure for MES. The macro-MESs interact energy in individual or integrated energy markets to maximize their profit through competing with other MEPs or conventional energy market players.

The mathematical model considers two layers of a macro-MES and its interior micro-MESs. The macro-MES operator participates in energy market as well as interacting energy with micro-MESs to maximize its profit. Moreover, micro-MESs utilize their local energy facilities to maximize their profit while participating in the local energy market (macro-MES environment) and satisfying their MEDs needs. MEPs interaction is designed in two layers; in the first layer local energy price will be determined based on MEPs energy interaction. In the second one, the micro-MESs schedule their internal energy balance based on pre-determined energy price. By implementing dual theorem, this bi-level mathematical problem will be transformed into a single level mathematical program with equilibrium constraint (MPEC). Therefore, the final problem is a single stage mix-integer linear problem (MILP) that can be solved by conventional MILP solvers (i.e. CPLEX12).

C. Literature Review

References [2] and [3] are two pioneer references that have respectively proposed *"Energy Hub System"* and *"Matrix Modeling"* approaches to model the cooperation environment in MES. In both approaches, the MES consists of some super-nodes that convert and store energy carriers and their corresponding interconnectors that transmit energy among super-nodes. Reference [4] has developed an optimal energy flow model for MES. The model has been developed in [5] and new optimization techniques have been implemented to guarantee the optimal solution.

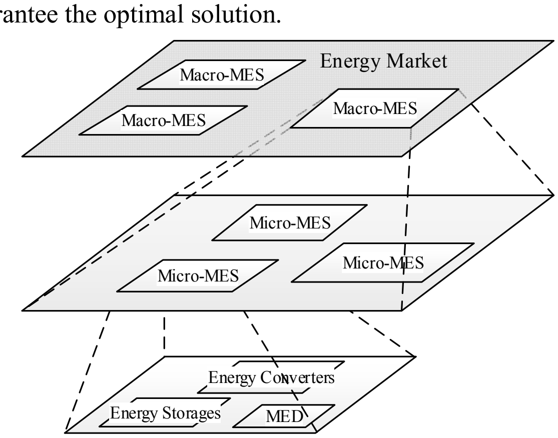

Fig. 1. A schematic of the multi-layer energy system.

Moreover, the optimal scheduling for residential and industrial energy hub has been modeled in [6] and [7], respectively.

Ref. [8] has modeled the cooperation environment among MEPs by architecting a decentralized agent based control system. Although the model has considered various features of MES from a technical point of view, the economic aspects have not been modeled properly. In the literature, micro-grids have the similar concept as MES and introduce operational flexibility to the system in normal and contingency operation modes. In [9], a multi-timescale framework has been proposed to mitigate intermittency of renewable energy resources by utilizing MES concept and various behavior of combined cooling, heating and power (CCHP) unit in a micro-grid.

Moreover, for a set of MGs, Ref. [10] uses an agent-based framework to model the cooperation environment among MGs. In this topic, Ref. [11] has implemented a reinforcement learning method to consider various MGs with different functionality and equipment. Moreover, the coalitional behavior of MGs in a game-based environment has been modeled in [12].

D. Paper Contributions and Organization

The main contributions of this paper are as follow:

- Proposing a fractal structure for MES;
- Modeling the decision making conflict among MEPs in the proposed structure through a bi-level framework.
- Transforming the nonlinear bi-level problem to a single level MILP problem by implementing dual theorem.

The organization of this paper is as follows. In Section III, MEPs objective function and constraints are formulated. The dual format of the second level of proposed bi-level problem and modeling procedure for transforming the problem into a single level problem is described in Section IV. In Section V the numerical result are illustrated and concluding remarks are presented in Section VI.

III. Multi-Energy Players Modeling

In this paper, the MEPs are considered as a macro-MES and its interior micro-MESs.

Fig. 2 sows energy and information interaction among MEPs in local and wholesale energy market.

A. Macro-MES Level

The macro-MES trades energy in predetermined energy prices ($\Pi_{e,t}^{Ma}$, $\Pi_{g,t}^{Ma}$) in wholesale electricity and gas market and interacts energy with micro-MESs in coupled energy prices ($\pi_{e,t}^{Mi}$, $\pi_{g,t}^{Mi}$, $\pi_{h,t}^{Mi}$).

$$f(x) = Max\left\{\sum_t\left[-\left(w_t^{Ma}\Pi_{e,t}^{Ma} + g_t^{Ma}\Pi_{g,t}^{Ma}\right) + \sum_i\left(w_{i,t}^{Mi}\pi_{e,t}^{Mi} + g_{i,t}^{Mi}\pi_{g,t}^{Mi} + q_{i,t}^{Mi}\pi_{h,t}^{Mi}\right)\right]\right\} \quad (1)$$

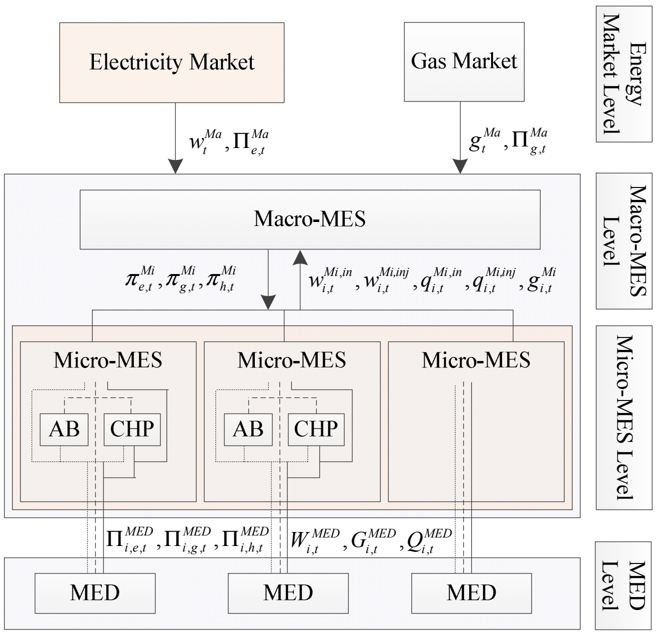

Fig. 2. Energy interaction among MEPs in MES.

Equations (2) and (3) demonstrate the limitations of macro-MES's interconnectors to interact with the energy market. Furthermore, (4)-(6) determine the energy balance in the macro-MES for electricity, gas, and district heating, respectively.

$$-\overline{W}^{Ma} \le w_t^{Ma} \le \overline{W}^{Ma} \tag{2}$$

$$0 \le g_t^{Ma} \le \overline{G}^{Ma} \tag{3}$$

$$w_t^{Ma} - \sum_i w_{i,t}^{Mi} = 0 \tag{4}$$

$$g_t^{Ma} - \sum_i g_{i,t}^{Mi} = 0 \tag{5}$$

$$\sum_i q_{i,t}^{Mi} = 0 \tag{6}$$

B. Micro-MES Level

Obj. Functions: micro-MESs are equipped with CHP units and auxiliary boilers (AB) and their objective functions consist of energy profit terms from interacting with macro-MES and MEDs.

$$\begin{aligned} Max \Bigg\{ \sum_t \Big[-\Big((w_{i,t}^{Mi,in} - w_{i,t}^{Mi,inj})\, \pi_{e,i,t}^{Mi} \\ +(q_{i,t}^{Mi,in} - q_{i,t}^{Mi,inj})\, \pi_{h,i,t}^{Mi} + g_{i,t}^{Mi}\, \pi_{g,i,t}^{Mi} \Big) \\ + W_{i,t}^{MED}\, \Pi_{e,i,t}^{MED} + G_{i,t}^{MED}\, \Pi_{g,i,t}^{MED} + Q_{i,t}^{MED}\, \Pi_{h,i,t}^{MED} \Big] \Bigg\} \end{aligned} \tag{7}$$

Energy balance constraints: The energy balance in each micro-MES should be preserved in each time interval (Eqs. (8)-(10)).

$$G_{i,t}^{MED} - g_{i,t}^{Mi,in} + g_{i,t}^{CHP} + g_{i,t}^{AB} = 0 \quad : \lambda_{g,i,t}^{MED} \tag{8}$$

$$Q_{i,t}^{MED} - q_{i,t}^{Mi,in} + q_{i,t}^{Mi,inj} - q_{i,t}^{CHP} - q_{i,t}^{AB} = 0 \quad : \lambda_{g,i,t}^{MED} \tag{9}$$

$$W_{i,t}^{MED} - w_{i,t}^{Mi,in} + w_{i,t}^{Mi,inj} - w_{i,t}^{CHP} = 0 \quad : \lambda_{g,i,t}^{MED} \tag{10}$$

Energy interaction constraints: The input and output energy to the micro-MESs are restricted by Eqs. (11)-(15).

$$0 \le w_{i,t}^{Mi,in} \le \overline{W}_i^{Mi} \quad : \underline{\mu}_{e,i,t}^{Mi,in}, \overline{\mu}_{e,i,t}^{Mi,in} \tag{11}$$

$$0 \le w_{i,t}^{Mi,inj} \le \overline{W}_i^{Mi} \quad : \underline{\mu}_{e,i,t}^{Mi,inj}, \overline{\mu}_{e,i,t}^{Mi,inj} \tag{12}$$

$$0 \le q_{i,t}^{Mi,in} \le \overline{Q}_i^{Mi} \quad : \underline{\mu}_{h,i,t}^{Mi,in}, \overline{\mu}_{h,i,t}^{Mi,in} \tag{13}$$

$$0 \le q_{i,t}^{Mi,inj} \le \overline{Q}_i^{Mi} \quad : \underline{\mu}_{h,i,t}^{Mi,inj}, \overline{\mu}_{h,i,t}^{Mi,inj} \tag{14}$$

$$0 \le g_{i,t}^{Mi,in} \le \overline{G}_i^{Mi} \quad : \underline{\mu}_{g,i,t}^{Mi,in}, \overline{\mu}_{g,i,t}^{Mi,in} \tag{15}$$

CHP unit constraints: Output heat and electricity in CHP unit is related to the unit's heat and electricity efficiency and its operational characteristics.

$$w_{i,t}^{CHP} - \eta_{e,i}^{CHP} g_{i,t}^{CHP} = 0 \quad : \lambda_{e,i,t}^{CHP} \tag{16}$$

$$q_{i,t}^{CHP} - \eta_{h,i}^{CHP} g_{i,t}^{CHP} = 0 \quad : \lambda_{h,i,t}^{CHP} \tag{17}$$

$$0 \le w_{i,t}^{CHP} \le \overline{W}_i^{CHP} \quad : \underline{\mu}_{e,i,t}^{CHP}, \overline{\mu}_{e,i,t}^{CHP} \tag{18}$$

$$0 \le q_{i,t}^{CHP} \le \overline{Q}_i^{CHP} \quad : \underline{\mu}_{h,i,t}^{CHP}, \overline{\mu}_{h,i,t}^{CHP} \tag{19}$$

$$w_{i,t}^{CHP} \varphi_i^{CHP} - q_{i,t}^{CHP} = 0 \quad : \lambda_{i,t}^{Ratio} \tag{20}$$

AB operational constraints: AB converts input gas to the output heat based on its thermal efficiency and operational limitations (Eqs. (21) and (22)).

$$q_{i,t}^{AB} - \eta_{h,i}^{AB} g_{i,t}^{AB} = 0 \quad : \lambda_{h,i,t}^{AB} \tag{21}$$

$$0 \le q_{i,t}^{AB} \le \overline{Q}_i^{AB} \quad : \underline{\mu}_{h,i,t}^{AB}, \overline{\mu}_{h,i,t}^{AB} \tag{22}$$

IV. MPEC Formulation of Problem

In this paper, the decision making process is considered in two levels. A bi-level approach has been reported in [13] and [14] based on the dual theorem to transform this kind of decision making conflict among an upper level decision maker and smaller ones in the lower level to a single level MILP problem. In this paper the procedure for solving this decision making conflict is as follow:

- The lower level problem (micro-MESs profit maximization) is transformed into a convex and linear problem.
- In the upper level problem, the coupling signal price is determined based on MEPs energy interaction.
- The deduced signal price from the upper level is considered as a parameter for lower level problem.
- The lower level problems are replaced by their Karush-Kuhn-Tucker (KKT) optimality conditions.
- Strong duality theorem is implemented to linearize the nonlinear terms of the upper level objective function.

Therefore, the Lagrangian expression of lower level problem is illustrated as eq. (23).

$$\begin{aligned}\ell = &\left(\left(w_{i,t}^{Mi,in} - w_{i,t}^{Mi,inj}\right)\pi_{e,i,t}^{Mi} + g_{i,t}^{Mi}\pi_{g,i,t}^{Mi} + \left(q_{i,t}^{Mi,in} - q_{i,t}^{Mi,inj}\right)\pi_{h,i,t}^{Mi}\right) + \\ &\lambda_{g,i,t}^{MED}\left(G_{i,t}^{MED} - g_{i,t}^{Mi} + g_{i,t}^{CHP} + g_{i,t}^{AB}\right) + \lambda_{h,i,t}^{MED}\left(Q_{i,t}^{MED} - q_{i,t}^{Mi,in} + q_{i,t}^{Mi,inj} - q_{i,t}^{CHP} - q_{i,t}^{AB}\right) + \lambda_{e,i,t}^{MED}\left(W_{i,t}^{MED} - w_{i,t}^{Mi,in} + w_{i,t}^{Mi,inj} - w_{i,t}^{CHP}\right) \\ &+ \lambda_{e,i,t}^{CHP}\left(w_{i,t}^{CHP} - \eta_{e,i}^{CHP} g_{i,t}^{CHP}\right) + \lambda_{h,i,t}^{CHP}\left(q_{i,t}^{CHP} - \eta_{h,i}^{CHP} g_{i,t}^{CHP}\right) + \lambda_{i,t}^{Ratio}\left(q_{i,t}^{CHP} - w_{i,t}^{CHP}\varphi_i^{CHP}\right) + \lambda_{h,i,t}^{AB}\left(q_{i,t}^{AB} - \eta_{h,i}^{AB} g_{i,t}^{AB}\right) + \\ &-\underline{\mu}_{e,i,t}^{Mi,in}\left(w_{i,t}^{Mi,in}\right) - \overline{\mu}_{e,i,t}^{Mi,in}\left(\overline{W}_i^{Mi} - w_{i,t}^{Mi,in}\right) - \underline{\mu}_{e,i,t}^{Mi,inj}\left(w_{i,t}^{Mi,inj}\right) - \overline{\mu}_{e,i,t}^{Mi,inj}\left(\overline{W}_i^{Mi} - w_{i,t}^{Mi,inj}\right) - \underline{\mu}_{h,i,t}^{Mi,in}\left(q_{i,t}^{Mi,in}\right) - \overline{\mu}_{h,i,t}^{Mi,in}\left(\overline{Q}_i^{Mi} - q_{i,t}^{Mi,in}\right) \\ &-\underline{\mu}_{h,i,t}^{Mi,out}\left(q_{i,t}^{Mi,inj}\right) - \overline{\mu}_{h,i,t}^{Mi,inj}\left(\overline{Q}_i^{Mi} - q_{i,t}^{Mi,inj}\right) - \underline{\mu}_{g,i,t}^{Mi}\left(g_{i,t}^{Mi}\right) - \overline{\mu}_{g,i,t}^{Mi}\left(\overline{G}_i^{Mi} - g_{i,t}^{Mi}\right) - \underline{\mu}_{e,i,t}^{CHP}\left(w_{i,t}^{CHP}\right) - \overline{\mu}_{e,i,t}^{CHP}\left(\overline{W}_i^{CHP} - w_{i,t}^{CHP}\right) \\ &-\underline{\mu}_{h,i,t}^{CHP}\left(q_{i,t}^{CHP}\right) - \overline{\mu}_{h,i,t}^{CHP}\left(\overline{Q}_i^{CHP} - q_{i,t}^{CHP}\right) - \underline{\mu}_{h,i,t}^{AB}\left(q_{i,t}^{AB}\right) - \overline{\mu}_{h,i,t}^{AB}\left(\overline{Q}_i^{AB} - q_{i,t}^{AB}\right)\end{aligned} \quad (23)$$

Moreover, Eqs. (24)-(33) are stationarity conditions for lower level problem. These equations are first derivative of Lagrangian expression with respect to the lower level decision making variables.

$$\frac{\partial \ell}{\partial w_{i,t}^{Mi,in}} = +\pi_{e,i,t}^{Mi} - \lambda_{e,i,t}^{MED} - \underline{\mu}_{e,i,t}^{Mi,in} + \overline{\mu}_{e,i,t}^{Mi,in} = 0 \quad (24)$$

$$\frac{\partial \ell}{\partial w_{i,t}^{Mi,inj}} = -\pi_{e,i,t}^{Mi} + \lambda_{e,i,t}^{MED} - \underline{\mu}_{e,i,t}^{Mi,inj} + \overline{\mu}_{e,i,t}^{Mi,inj} = 0 \quad (25)$$

$$\frac{\partial \ell}{\partial q_{i,t}^{Mi,in}} = +\pi_{h,i,t}^{Mi} - \lambda_{h,i,t}^{MED} - \underline{\mu}_{h,i,t}^{Mi,in} + \overline{\mu}_{h,i,t}^{Mi,in} = 0 \quad (26)$$

$$\frac{\partial \ell}{\partial q_{i,t}^{Mi,inj}} = -\pi_{h,i,t}^{Mi} + \lambda_{h,i,t}^{MED} - \underline{\mu}_{h,i,t}^{Mi,inj} + \overline{\mu}_{h,i,t}^{Mi,inj} = 0 \quad (27)$$

$$\frac{\partial \ell}{\partial g_{i,t}^{Mi}} = +\pi_{g,i,t}^{Mi} - \lambda_{g,i,t}^{MED} - \underline{\mu}_{g,i,t}^{Mi} + \overline{\mu}_{g,i,t}^{Mi} = 0 \quad (28)$$

$$\frac{\partial \ell}{\partial w_{i,t}^{CHP}} = -\lambda_{e,i,t}^{MED} + \lambda_{e,i,t}^{CHP} - \lambda_{i,t}^{Ratio}\varphi_i^{CHP} - \underline{\mu}_{e,i,t}^{CHP} + \overline{\mu}_{e,i,t}^{CHP} = 0 \quad (29)$$

$$\frac{\partial \ell}{\partial q_{i,t}^{CHP}} = -\lambda_{h,i,t}^{MED} + \lambda_{h,i,t}^{CHP} + \lambda_{i,t}^{Ratio} - \underline{\mu}_{h,i,t}^{CHP} + \overline{\mu}_{h,i,t}^{CHP} = 0 \quad (30)$$

$$\frac{\partial \ell}{\partial g_{i,t}^{CHP}} = \lambda_{g,i,t}^{MED} - \lambda_{h,i,t}^{AB}\eta_{h,i}^{AB} = 0 \quad (31)$$

$$\frac{\partial \ell}{\partial q_{i,t}^{AB}} = -\lambda_{h,i,t}^{MED} + \lambda_{h,i,t}^{AB} - \underline{\mu}_{h,i,t}^{AB} + \overline{\mu}_{h,i,t}^{AB} = 0 \quad (32)$$

$$\frac{\partial \ell}{\partial g_{i,t}^{AB}} = \lambda_{g,i,t}^{MED} - \lambda_{e,i,t}^{CHP}\eta_{e,i}^{CHP} - \lambda_{h,i,t}^{CHP}\eta_{h,i}^{CHP} = 0 \quad (33)$$

In addition, inequalities (34)-(49) demonstrates complementary conditions for non-equality constraints of lower level problem.

$$0 \le \underline{\mu}_{e,i,t}^{Mi,in} \perp w_{i,t}^{Mi,in} \ge 0 \quad (34)$$

$$0 \le \overline{\mu}_{e,i,t}^{Mi,in} \perp \left(\overline{W}_i^{Mi} - w_{i,t}^{Mi,in}\right) \ge 0 \quad (35)$$

$$0 \le \underline{\mu}_{e,i,t}^{Mi,inj} \perp w_{i,t}^{Mi,inj} \ge 0 \quad (36)$$

$$0 \le \overline{\mu}_{e,i,t}^{Mi,inj} \perp \left(\overline{W}_i^{Mi} - w_{i,t}^{Mi,inj}\right) \ge 0 \quad (37)$$

$$0 \le \underline{\mu}_{h,i,t}^{Mi,in} \perp q_{i,t}^{Mi,in} \ge 0 \quad (38)$$

$$0 \le \overline{\mu}_{h,i,t}^{Mi,in} \perp \left(\overline{Q}_i^{Mi} - q_{i,t}^{Mi,in}\right) \ge 0 \quad (39)$$

$$0 \le \underline{\mu}_{h,i,t}^{Mi,out} \perp q_{i,t}^{Mi,inj} \ge 0 \quad (40)$$

$$0 \le \overline{\mu}_{h,i,t}^{Mi,inj} \perp \left(\overline{Q}_i^{Mi} - q_{i,t}^{Mi,inj}\right) \ge 0 \quad (41)$$

$$0 \le \underline{\mu}_{g,i,t}^{Mi} \perp g_{i,t}^{Mi} \ge 0 \quad (42)$$

$$0 \le \overline{\mu}_{g,i,t}^{Mi} \perp \left(\overline{G}_i^{Mi} - g_{i,t}^{Mi}\right) \ge 0 \quad (43)$$

$$0 \le \underline{\mu}_{e,i,t}^{CHP} \perp w_{i,t}^{CHP} \ge 0 \quad (44)$$

$$0 \le \overline{\mu}_{e,i,t}^{CHP} \perp \left(\overline{W}_i^{CHP} - w_{i,t}^{CHP}\right) \ge 0 \quad (45)$$

$$0 \le \underline{\mu}_{h,i,t}^{CHP} \perp q_{i,t}^{CHP} \ge 0 \quad (46)$$

$$0 \le \overline{\mu}_{h,i,t}^{CHP} \perp \left(\overline{Q}_i^{CHP} - q_{i,t}^{CHP}\right) \ge 0 \quad (47)$$

$$0 \le \underline{\mu}_{h,i,t}^{AB} \perp q_{i,t}^{AB} \ge 0 \quad (48)$$

$$0 \le \overline{\mu}_{h,i,t}^{AB} \perp \left(\overline{Q}_i^{AB} - q_{i,t}^{AB}\right) \ge 0 \quad (49)$$

The conflict among decision making of upper level macro-MES and lower level micro-MESs depends to their energy interaction and the energy carriers' coupling prices ($w_{i,t}^{Mi,in}\pi_{e,i,t}^{Mi}$, $w_{i,t}^{Mi,inj}\pi_{e,i,t}^{Mi}$, $g_{i,t}^{Mi}\pi_{g,i,t}^{Mi}$, $q_{i,t}^{Mi,in}\pi_{h,i,t}^{Mi}$, and $q_{i,t}^{Mi,inj}\pi_{h,i,t}^{Mi}$,).

These terms are nonlinear terms of upper level problem that can be linearized by implementing strong duality condition. The strong duality condition states that in optimality condition the gap between primal and dual objective functions are less than pre-determined error and these two objective functions can be considered as equal.

Equation (50) determines strong duality condition for lower level problem.

$$\begin{aligned}&w_{i,t}^{Mi,in}\pi_{e,i,t}^{Mi} - w_{i,t}^{Mi,inj}\pi_{e,i,t}^{Mi} + q_{i,t}^{Mi,in}\pi_{h,i,t}^{Mi} - q_{i,t}^{Mi,inj}\pi_{h,i,t}^{Mi} + g_{i,t}^{Mi}\pi_{g,i,t}^{Mi} = \\ &G_{i,t}^{MED}\lambda_{g,i,t}^{MED} + Q_{i,t}^{MED}\lambda_{h,i,t}^{MED} + W_{i,t}^{MED}\lambda_{e,i,t}^{MED} + \overline{W}_i^{Mi}\overline{\mu}_{e,i,t}^{Mi,in} \\ &+\overline{W}_i^{Mi}\overline{\mu}_{e,i,t}^{Mi,inj} + \overline{Q}_i^{Mi}\overline{\mu}_{h,i,t}^{Mi,in} + \overline{Q}_i^{Mi}\overline{\mu}_{h,i,t}^{Mi,inj} + \overline{G}_i^{Mi}\overline{\mu}_{g,i,t}^{Mi} \\ &+\overline{W}_i^{CHP}\overline{\mu}_{e,i,t}^{CHP} + \overline{Q}_i^{CHP}\overline{\mu}_{h,i,t}^{CHP} + \overline{Q}_i^{AB}\overline{\mu}_{h,i,t}^{AB}\end{aligned} \quad (50)$$

V. Numerical Results

The MEPs in this paper are a macro-MES and its three interior micro-MESs (Fig. 1).

Two micro-MESs are equipped with CHP units and ABs and the third one just delivers energy to its MED. The price cap for gas and electricity are assumed as 0.05 and 0.13 (€/kWh) in macro-MES, respectively. Table I shows input data for micro-MESs.

Fig. 3 depicts the price signal in macro-MES environment and Figs. 4 shows total demand of macro-MES and its input electricity. Moreover, Figs. 5 and 6 demonstrate electricity and heat balance in the first micro-MES.

In the proposed model, the MEPs compete for gas and electricity to maximize their profit. Gas is supply just by macro-MES and cannot be produced locally. Therefore, most of the time its price is equal to price cap. On the other hand, micro-MESs can generate electricity locally and consequently, the electricity price is related to the gas price and heat consumption as well as system electricity consumption.

As a matter of fact, the electricity price is related to the operational flexibility of micro-MESs to generate cheaper electricity as a rival of macro-MES.

In hours 5 and 20, while the system has maximum heat demand and the electricity consumption is not so high, the micro-MESs participate in demand delivery and macro-MES maximizes its profit with increasing the electricity price. In hours 11 and 12 while the system has its maximum heat and electricity demand simultaneously the marginal cost for CHP unit productions is minimized.

Therefore, the macro-MES decrease both gas and electricity price to motivate micro-MESs to generate heat demand from AB and purchase their electricity needs from macro-MES.

TABLE I
Data of Micro-MESs' Elements

Elements		Micro-MES 1	Micro-MES 2	Micro-MES 3
Interconnectors	Transformer	0.95	0.95	0.95
	Heat Pipelines Efficiency	0.9	0.9	0.9
CHP	Output Electricity	400 kW	350 kW	---
	Output Heat	500 kW	500 kW	---
	$\eta_e^{CHP}, \eta_h^{CHP}$	0.45, 0.35	0.47, 0.3	---
AB	Output Heat	600 kW	600 kW	---
	η_h^{AB}	0.9	0.85	0.9

As it is shown in Fig. 4 each time that the micro-MESs have heat demand, due to lower marginal cost of local electricity generation, the macro-MES has minimum input electricity and vice versa.

The numerical results determine that the competitive environment in macro-MES motivates micro-MESs to utilize more their local energy resources and, consequently, micro-MESs flexibility to satisfy part of their demands motivates macro-MES to decrease the energy price. Moreover, the case study shows by putting an appropriate price cap for gas that the regulator can also prevent violation in the electricity price.

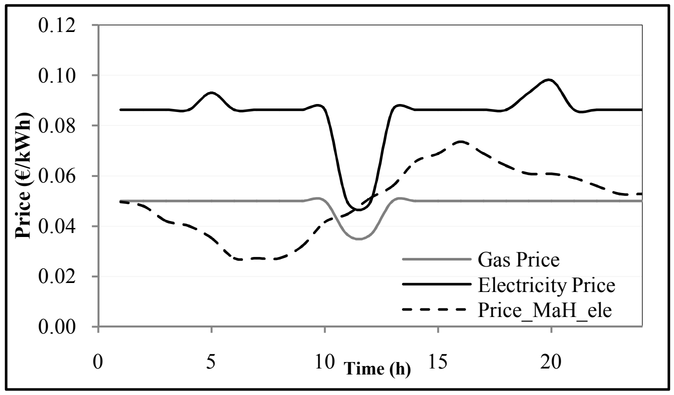

Fig. 3. Competitive signal price in macro-MES environment.

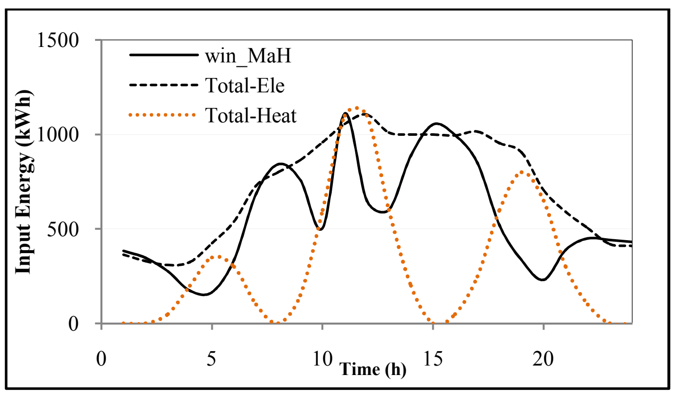

Fig. 4. Total demand and input electricity to the macro-MES.

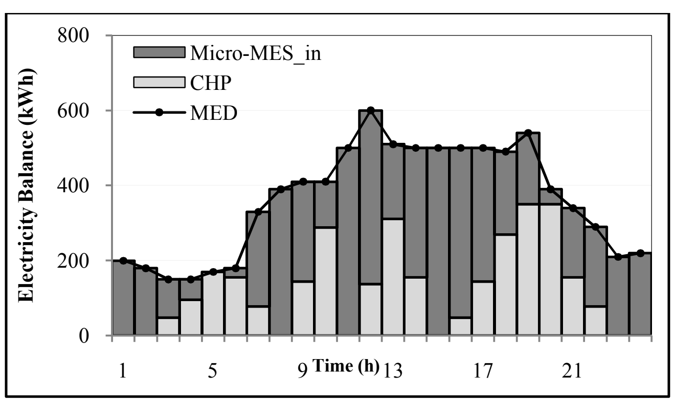

Fig. 5. Electricity balance in first micro-MES.

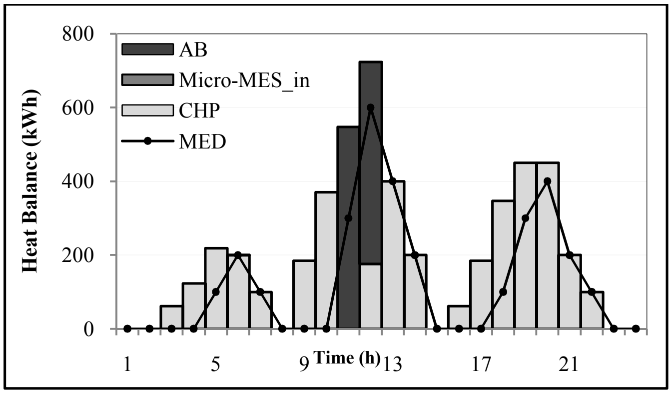

Fig. 6. Heat balance in first micro-MES.

VI. Conclusion

In this paper, a fractal structure has been proposed for decision making in MES. The decision making conflict among two layers of the proposed structure (i.e. macro-MES and its interior micro-MESs) has been modeled by implementing a bi-level approach. The non-linear bi-level problem has been transformed to a single level MILP problem by utilizing dual theorem. Numerical results have demonstrated the behavior of MEPs in the competitive environment. The flexibility of micro-MESs to change their energy interaction pattern mitigated market power of macro-MES and preserved electricity price less than marginal cost of micro-MESs electricity generation. Moreover, the results ascertained the impact of local resources operational condition (e.g. heat demand consumption for micro-MESs) on the capability of micro-MESs to rival with other MEPs. As a matter of fact, due to variable heat demand, micro-MESs have variable marginal cost for electricity generation in the operational time horizon.

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