Assessing the Effectiveness of Decision Making Frameworks in Local Energy Systems

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***Abstract*—This paper investigates the effectiveness of using different decision-making frameworks in local energy systems (LES) through the assessment of the long-term equilibrium of energy players. For this purpose, the energy system is modelled through two levels of multi-energy player (MEP) and LES, coupled by energy price signals. The conflict between the decision-making of these two levels of players is modelled through a bi-level approach. A mathematical problem with equilibrium constraints is formulated by applying the duality theory, resorting to a linear representation of the constraints. The solution is found by using the CPLEX12 solver. The numerical results show the characteristics of the MEP behaviour in different energy aggregation modes for the LES, with centralised management or uniform pricing. The MEP may find benefits from possible synergies among the LES due to the availability of energy carriers with complementary characteristics.**

***Index Terms*— Distributed energy resources, duality theory, local energy systems, mathematical programming, multi-energy player, multi-energy system.**

NOMENCLATURE

A. Subscripts

e	Electricity
g	Natural gas
h	Heat
i	Local energy system (LES)
n	Constraint
t	Time interval

B. Superscripts

EM	Electricity wholesale market
GM	Gas wholesale market
IL	Interruptible load
LES	Local energy system
MEP	Multi-energy player
MED	Multi-energy demand

C. Parameters and Variables

b	Benefit
c	Cost
g, G	Amount of natural gas supply
q, Q	Amount of heat production
u	Binary variable
w, W	Amount of electricity generation
A	Number of energy storage units
B	Number of energy converters
I	Number of local energy systems (LES)
L	Lagrangian function
M^p, M^d	Very big parameter for the relaxation of primal and dual constraints
N	Number of constraints
S	Number of energy storage units
T	Time period
λ	Dual variables for equality constraints
$\bar{\mu}$, $\underline{\mu}$	Dual variables for the upper and lower limits of non-equality constraints
ξ	Dual variables for equality constraints in specific time intervals
π, Π	Energy price

D. Vectors

$\mathbf{b}$	Vector of constant right hand-side of constraints
$\mathbf{e}$	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
$\boldsymbol{\psi}$	Vector of dual variables
$\mathbf{H}$	Matrix of decision variables coefficients

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

The evolution of emergent demand side technologies, together with the changing business paradigms in the energy sector, have introduced new challenges and opportunities to the operators for supplying the energy needs. The extension of Distributed Energy Resources (DER) with energy converters and storage systems has increased the usage of multiple energy carriers, and has enabled advanced operation strategies in the time domain. On the other hand, the establishment of new business competition environments (e.g., energy markets), with the participation of more players to the energy system decision-making process, has increased the dependency of the market outcomes on the decision variables of various stakeholders. Recent researches on the concept of Multi-Energy Systems (MES) consider the interactions among energy carriers and decision-making entities in this interdependent environment.

In the literature, MES have been defined as energy systems containing more than one energy carrier [1]. A MES contains various energy resources, converters and storage systems. Integrated MES modelling has been proposed under the energy hub paradigm, considering some equipment and their interconnectors [2]. The energy hub (mostly consisting of co- or tri-generation systems, including energy storage) is modelled as a black box, in which the input energy carriers are converted into the demanded energy services. The interconnectors transmit energy among the equipment, and from the mathematical point of view share the input variables of the energy hubs. The matrix modelling presented in [3] utilises the same mathematical modelling approach, but the input and output vectors contain the same quantities, which helps the developers to easily add new elements to the model.

To model the energy interactions of energy hubs and their interconnectors, reference [4] proposed an integrated optimal power flow for gas and electricity networks. In the solution procedure developed in [5], a multi-agent genetic algorithm has been used to cope with large-scale non-linear problem, to reduce the computation time and increase the accuracy of the results. Reference [6] proposed a decentralised control framework for modelling the cooperation environment of energy hubs in MES. Although the model considered various features of MES from the technical point of view, the economical aspects were not modelled.

II. Problem Statement

The main problem addressed in this paper deals with the mutual behaviour of a multi-energy player (MEP) and local energy system (LES) in energy distribution networks based on various possible energy interaction frameworks. MES are considered in four layers, namely, wholesale energy markets, MEP, LES, and multi-energy demand (MED) [7]. The LES are equipped with distributed energy resources (DER) and interact with the energy carriers (e.g., electricity, gas, and heat), with other LES, and the MEP. The MEP behaves as an energy aggregator that facilitates energy and financial interactions between the LES and the upstream wholesale energy markets. In addition, two energy interaction frameworks, namely, centralised management of LES and uniform pricing, are compared in this proposed structure. Moreover, in the competitive management mode, the behaviour of the energy players is investigated for energy carrier price changes.

In this paper, a specific index is proposed to assess the effectiveness of the proposed frameworks to aggregate LES. Moreover, a bi-level approach has been adopted to model the behaviour of MEP and LES in the MES. In the upper level, the MEP maximises its profit while satisfying the LES energy exchange. The coupling variables between MEP and LES are the energy prices that are determined based on the strategic behaviour of the energy players in the local energy network. Then, each LES schedules its energy balance based on the upper level price signal and determines the quantity of exchanged energy. The problem is transformed into a mathematical problem with equilibrium constraints. The resulting programming model is solved with the CPLEX 12 solver called by the GAMS software.

III. Mathematical Formulation of the MES Model

A. MEP Objective function and Constraints

Objective Function: The MEP aggregates the energy trade of the LES and manages the energy exchange among them. The objective of the MEP is maximising its profit resulting from the energy exchange with its LES and the wholesale energy market. The operator is considered as a price taker in the energy market and trades energy (i.e., gas and electricity) at predetermined prices, $\Pi_{e,t}^{MEP}$ for electricity and $\Pi_{g,t}^{MEP}$ for gas. On the other hand, the MEP determines the coupling price among LES. The maximisation of the MEP profit contains the following components:

- Energy costs at time interval t, depending on the electricity and gas purchased from the corresponding wholesale markets:

$$c_t^{MEP} = w_t^{MEP}\Pi_{e,t}^{EM} + g_t^{MEP}\Pi_{g,t}^{GM} \tag{1}$$

- Benefits from selling energy at time interval t, depending on the electricity, gas and heat sold by the MEP to the i-th LES:

$$b_t^{MEP} = \sum_{i=1}^{I}\left(w_{i,t}^{LES}\pi_{e,i,t}^{MEP} + g_{i,t}^{LES}\pi_{g,i,t}^{MEP} + q_{i,t}^{LES}\pi_{h,i,t}^{MEP}\right) \tag{2}$$

The MEP profit is determined by the difference of benefits and costs, and its maximisation is expressed as follows:

$$\max\{\textstyle\sum_{t=1}^{T}(b_t^{MEP} - c_t^{MEP})\} \tag{3}$$

Constraints: The constraints for the MEP include its energy contract provisions and the restrictions due to the energy exchange limits for electricity and gas.

B. LES Objective function and Constraints

Objective Function: The objective of each LES is to maximise its profit from selling energy to the MED and trading energy with the MEP, while meeting the operational constraints of its internal energy elements. The decision variables for the i-th LES are included in the vector $\mathbf{x}_i$. The term $f_i(\mathbf{x}_i)$ represents the objective function for the i-th LES and is optimised based on their internal energy schedule and the energy exchange at the MEP level. Instead of maximising the profit, the problem is formulated by minimising the minus-profit, as indicated in [8].

The energy cost for the *i*-th LES in the time interval *t* is expressed as:

$$c_{i,t}^{LES} = w_{i,t}^{LES}\pi_{e,i,t}^{MEP} + g_{i,t}^{LES}\pi_{g,i,t}^{MEP} + q_{i,t}^{LES}\pi_{h,i,t}^{MEP} \quad (4)$$

The benefit for the *i*-th LES from selling the energy to the MED is represented as:

$$b_{i,t}^{LES} = \left(W_{i,t}^{MED} - w_{i,t}^{IL}\right)\Pi_{e,i,t}^{MED} + G_{i,t}^{MED}\Pi_{g,i,t}^{MED} + Q_{i,t}^{MED}\Pi_{h,i,t}^{MED} - w_{i,t}^{IL}\Pi_{i,t}^{IL} \quad (5)$$

where $\Pi_{i,t}^{IL}$ represents the incentive given in the time interval *t* to the interruptible load service provided by the MED, being $w_{i,t}^{IL}$ the electrical load reduction.

The LES minus-profit is determined by the difference of costs and benefits, and its minimisation is expressed as follows:

$$\min\left\{f_i(\mathbf{x}_i) = \sum_{t=1}^{T}\left(c_{i,t}^{LES} - b_{i,t}^{LES}\right)\right\} \quad (6)$$

Constraints: A LES may contain combined heat and power unit, auxiliary boiler, renewable energy sources (RES), heat storage, and interruptible load resources. The operational constraints of these units are considered as LES constraints [9].

The Equations (7)-(9) present the general form of the optimisation problem for a LES, written in the classical matrix representation, with the equality constraints $\mathbf{e}_i(\mathbf{x}_i)$ and the inequality constraints $\mathbf{n}_i(\mathbf{x}_i)$.

$$\min\{f_i(\mathbf{x}_i)\} \quad (7)$$

$$\text{s.t. } \mathbf{e}_i(\mathbf{x}_i) = \mathbf{0} \quad (8)$$

$$\mathbf{n}_i(\mathbf{x}_i) \geq \mathbf{0} \quad (9)$$

$$\mathbf{x}_i \geq \mathbf{0} \quad (10)$$

By using a linear representation of the constraints equations, based on the introduction of the matrices $\mathbf{H}_{\mathbf{e}_i}$ and $\mathbf{H}_{\mathbf{n}_i}$ containing the coefficients for the equality and inequality constraints, respectively, it is possible to rewrite the equations (8) and (9) as:

$$\mathbf{H}_{\mathbf{e}_i}\,\mathbf{x}_i = \mathbf{0} \quad (11)$$

$$\mathbf{H}_{\mathbf{n}_i}\,\mathbf{x}_i - \mathbf{b}_{\mathbf{n}_i} \geq \mathbf{0} \quad (12)$$

With a further step in which the following terms are defined:

$$\mathbf{H}_i = \begin{bmatrix}\mathbf{H}_{\mathbf{e}_i}\\ \mathbf{H}_{\mathbf{n}_i}\end{bmatrix}; \quad \mathbf{b}_i = \begin{bmatrix}\mathbf{0}\\ \mathbf{b}_{\mathbf{n}_i}\end{bmatrix} \quad (13)$$

the constraints are expressed in a synthetic form as follows:

$$\mathbf{H}_i\,\mathbf{x}_i - \mathbf{b}_i \geq \mathbf{0} \quad (14)$$

C. Interactive Decision-Making for MEP and LES

The formulation proposed is based on a decision-making framework in which the MEP and the LES are active at two different levels, but need to interact as they share some decision variables. The model can be considered as a Stackelberg game (in which one player - the leader - moves first, and all the other players - the followers - move next [10]). In particular, at the upper level there is a MEP as the leader, and at the lower level there are LES as followers. The MEP determines the energy price, on the basis of which the LES find how to schedule their internal energy resources and propose the energy exchanges according with the price signals. This bi-level problem is of Mixed Integer Non-Linear Programming (MINLP) type, and can be transformed into a single level Mixed Integer Linear Programming (MILP) problem on the basis of the following procedure [11][12]:

- consider the upper level price signal as an input parameter for the lower level;
- transform each lower level (LES) problem into a convex and linear problem;
- replace the lower level problems by their Karush-Kuhn-Tucker (KKT) optimality conditions;
- implement the strong duality theorem to linearize the nonlinear terms of the upper level objective function (i.e., $w_{i,t}^{LES}\pi_{e,i,t}^{MEP}$, $g_{i,t}^{LES}\pi_{g,i,t}^{MEP}$, and $q_{i,t}^{LES}\pi_{h,i,t}^{MEP}$).

D. Problem formulation at the LES Level

The LES equations are linear and thus convex. For replacing the lower level (LES) problem with its KKT optimality conditions, the Lagrangian expression of the lower level problem is determined as:

$$L_i = f_i(\mathbf{x}_i) + \boldsymbol{\lambda}_i^{\mathrm{T}}\,\mathbf{e}_i(\mathbf{x}_i) - \boldsymbol{\mu}_i^{\mathrm{T}}\,\mathbf{n}_i(\mathbf{x}_i) + \boldsymbol{\xi}_i^{\mathrm{T}}\,\mathbf{t}_i(\mathbf{x}_i) \quad (15)$$

where $\boldsymbol{\lambda}_i$, $\boldsymbol{\mu}_i$ and $\boldsymbol{\xi}_i$ are the vectors containing the dual variables of the LES equality constraints $\mathbf{e}_i(\mathbf{x}_i)$, inequality constraints $\mathbf{n}_i(\mathbf{x}_i)$, and equality constraints $\mathbf{t}_i(\mathbf{x}_i)$ in specific time intervals, respectively.

Taking the derivatives of the Lagrangian expression, Equations (16)-(19) represent the KKT conditions of the lower level problem. In particular, Equation (16) is the stationarity condition, Equations (17) and (18) are the primal feasibility conditions, and Equation (19) is the complementarity condition.

$$\frac{\partial L_i}{\partial \mathbf{x}_i} = \mathbf{0} \quad (16)$$

$$\frac{\partial L_i}{\partial \boldsymbol{\lambda}_i} = \mathbf{e}_i(\mathbf{x}_i) = \mathbf{0} \quad (17)$$

$$\frac{\partial L_i}{\partial \boldsymbol{\xi}_i} = \mathbf{t}_i(\mathbf{x}_i) = \mathbf{0} \quad (18)$$

$$\mathbf{0} \leq \boldsymbol{\mu}_i \perp \mathbf{n}_i(\mathbf{x}_i) \geq \mathbf{0} \quad (19)$$

For linearizing the complementarity conditions, a set of binary variables ($\mathbf{u}_i$) are implemented to transform the equation (19) into the Equations (20) and (21), by introducing two large constant values M^p and M^d [10].

$$\mathbf{0} \leq \mathbf{n}_i(\mathbf{x}_i) \leq \mathbf{u}_i M^p \quad (20)$$

$$\mathbf{0} \leq \boldsymbol{\mu}_i \leq \mathbf{u}_i M^d \quad (21)$$

E. Primal and dual problems

For the solution of the lower level problem, the objective function may be written as $f_i(\mathbf{x}_i) = \mathbf{c}_i^{\mathrm{T}}\,\mathbf{x}_i$, ignoring all constant entries and introducing in the coefficients vector $\mathbf{c}_i$ the multipliers of the decision variables $\mathbf{x}_i$. Then, considering the primal problem $\min\{\mathbf{c}_i^{\mathrm{T}}\,\mathbf{x}_i\}$, subject to (14) and (10), the dual problem is written as [13]:

$$\max\{\mathbf{b}_i^{\mathrm{T}}\,\boldsymbol{\psi}_i\} \quad (22)$$

$$\mathbf{H}_i^{\mathrm{T}}\,\boldsymbol{\psi}_i - \mathbf{c}_i \leq \mathbf{0} \quad (23)$$

$$\boldsymbol{\psi}_i \geq \mathbf{0} \quad (24)$$

For a linear (and thus convex) problem, the strong duality theorem [13] guarantees that in the solution point the objective functions of the primal and dual problems are equal.

F. Single level problem

The single level problem is then formulated by minimizing the objective function $f_i(\mathbf{x}_i)$ in (6), subject to [12]:

- the constraints of the upper level problem;
- the primal constraints of the lower level problem;
- the dual constraints of the lower level problem;
- the strong duality equality of the primal-dual transformation, corresponding to the equality of the values obtained at the optimal solution of the primal and dual objective functions, equivalent to the KKT complementarity conditions linearized as indicated in (20) and (21).

IV. System Effectiveness Index and Energy Aggregation Modes

A. System Effectiveness Index

The main role of MES is enhancing the efficiency of the energy system by utilising all the energy resources, simultaneously. Therefore, in this paper the efficiency of MES to deliver the requested energy demand by utilising various energy vectors is considered as the system effectiveness index.

The system effectiveness index, denoted as Local Resource Utilisation Factor (*LRUF*) is related to the capability of LES to utilise their internal energy resources instead of importing energy from upstream network. Equation (22) shows the general format to calculate this index for the electricity carrier that will be delivered to MED, depending on two contributions:

$$LRUF_e = \frac{1}{T(A+S)}(ECEC_e + ECES_e) \tag{25}$$

For energy converters, the contribution to the index is based on the share of output energy to the maximum capacity of energy converter in the study time period, denoted as the Efficiency Contribution of the Energy Converters (*ECEC*):

$$ECEC_e = \sum_{\beta=1}^{S} \sum_{t=1}^{T} \frac{E_{\beta,e,t}}{\bar{E}_{\beta,e}} \tag{26}$$

On the other hand, the effectiveness of energy storage to mitigate the variation of the system is considered as the variation of the normalised energy level of storage in consecutive time intervals, leading to the Efficiency Contribution of the Energy Storage (*ECES*):

$$ECES_e = \sum_{\alpha=1}^{A} \sum_{t=1}^{T} \frac{|E_{\alpha,e,t} - E_{\alpha,e,t-1}|}{\bar{E}_{\alpha,e}} \tag{27}$$

The same formulation may be adopted from other energy carriers, by replacing for example the subscript *e* for electricity with *h* for heat.

B. Energy Aggregation Modes

The following *modes* are considered in this paper for energy aggregation of LES by MEP.

I. *Centralised management for LES:* In this aggregation mode the MEP manages all the energy facilities of LES. This mode is related to the capability of MEP to have at least one-way communication with LES to send the operation mode of each element. Although this mode needs vast communication infrastructure, it will reduce the planning cost for the whole system by exploiting the synergy among LES.

II. *Uniform pricing for LES:* In this aggregation mode, all the LES receive the same equilibrium price for each energy carrier. Therefore, instead of having various energy prices for each LES (i.e., $\pi_{e,i,t}^{MEP}$, $\pi_{g,i,t}^{MEP}$, and $\pi_{h,i,t}^{MEP}$) the energy prices ($\pi_{e,t}^{MEP}$, $\pi_{g,t}^{MEP}$, and $\pi_{h,t}^{MEP}$) are the same for all LES.

V. Numerical Applications

A. Input Data Characterisation

In this paper, the MEP has three interior LES (Fig. 1). It is assumed that the MEP is a price taker in the energy market and its interaction with other energy players has no impact on the input energy prices. Therefore, its interaction with other players in energy market is based on the predetermined energy carriers' price signals (Fig. 2). Network losses are not considered (single-busbar model used for all energy carriers).

Data of electricity price for input of MEP have been obtained from the hourly data of the Spanish electricity market in May 2015 [14]. Moreover, the LES interact energy with the MEP and serve the energy to the MED. The LES contain CHP (with multiple units), AB, HS, IL, and RES.

The comprehensive data for elements of the three LES are represented in Table I. The MILP problem has been solved by CPLEX12 solver called from the GAMS package with an HP Z800 Workstation, CPU: 3.47 GHz, RAM: 96 GB.

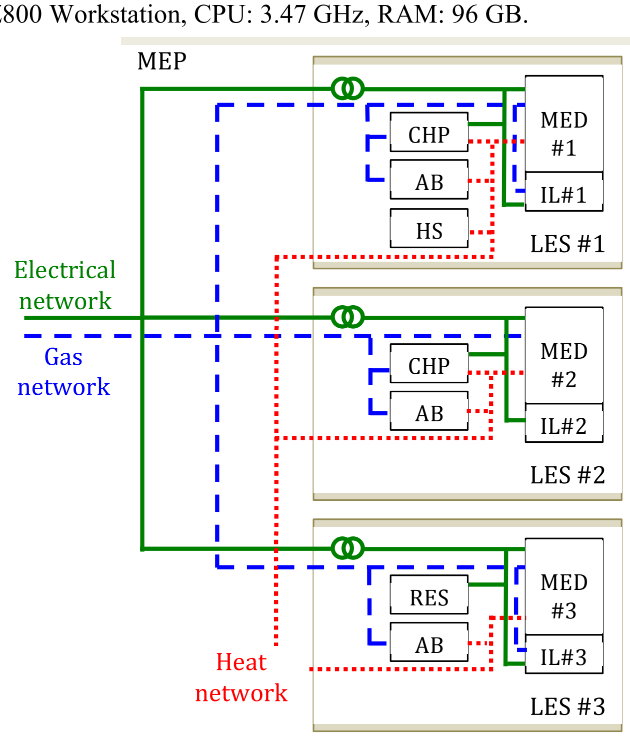

Fig. 1. Scheme with MEP and LES, with external electricity and gas supply.

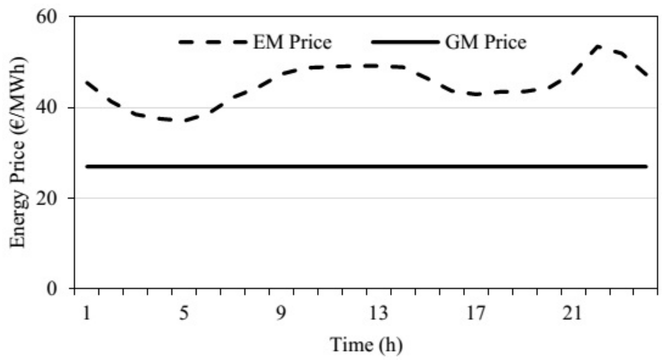

Fig. 2. Hourly prices in the electricity market (EM) and gas market (GM).

TABLE I. DATA OF THE LOCAL ENERGY SYSTEMS

Elements		LES#1	LES#2	LES#3
networks	Transformer efficiency	0.95	0.95	0.95
	Heat pipelines efficiency	0.9	0.9	0.9
CHP	Electricity output	2.5 MW	1.5 MW	--
	Heat output	3 MW	2.2 MW	--
	Electrical efficiency	0.43	0.45	--
	Thermal efficiency	0.35	0.3	--
AB	Heat output	2 MW	3 MW	1.5 MW
	Thermal efficiency	0.9	0.85	0.9
HS	Energy capacity	3 MWh	--	--
	Charge/discharge rate	1.5 MW	--	--
	Charging efficiency	0.9	--	--
	Discharging efficiency	0.81	--	--
RES	Wind capacity	--	--	3.3 MW
	PV capacity	--	--	3.3 MW

B. Uniform Pricing for LES

Between the two modes, the *Uniform pricing* is the most interactive one, in which MEP and LES schedule their energy balance on the basis of the same equilibrium price. Some details are presented here on the solution obtained for this mode. Fig. 3 shows the equilibrium price for the energy carriers (electricity, heat, and gas). Because of the same price for all LES in this framework, the equilibrium is formed based on the characteristics of all LES, and has more variations. Natural gas is supplied only by the MEP. Since the price cap on the gas price is relatively low with respect to the prices of the other energy carriers, and the MEP objective is to maximise its profit, the gas price is set up to its price cap during the entire day.

Fig. 4 shows the contributions of the various units to the LES electricity balance. Wind and PV are dispatched with the highest priority. Different MEP and LES behaviours appear in different time periods, which may be interpreted as follows:

a) The energy price is set to the marginal cost of the CHP units to increase the market share and total profit of the MEP; this happens at hours 3, 4, and 13 to 16.

b) From hour 5 to hour 8, the equilibrium price is increased to maximise the MEP profit by buying electricity at a relatively low EM price and selling at the maximum price the remaining LES energy. In this case, the equilibrium is reached with a small interruptible load curtailment (at IL#1 and IL#2), determining the change from the initial Demand to Demand (new).

c) In the period from hour 9 to hour 12, the EM price is high and the RES production is high (i.e., the marginal cost of electricity production for LES is low). It is then convenient for the MEP to buy electricity at lower price from LES and inject the surplus energy from the LES into the network, selling it to the electricity market to maximise the MEP profit.

d) During the rest of the day, and in general, the solutions are consistent with the evolution of the energy demand and prices. For example, at hours 18 and 19 it is profitable for the MEP to run the CHP units for producing heat, selling electricity to the market even if the electricity price is relatively low). In fact, when the LES generate electricity, they buy from the MEP the natural gas to run the CHP units. The solution is found when the net energy that the MEP is exchanging with the wholesale electricity market and the LES is profitable for both the MEP (at the upper level) and the LES (at the lower level).

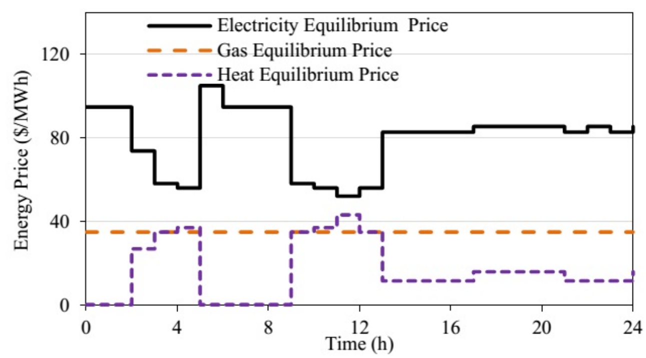

Fig. 3. Electricity equilibrium price between MEP and LES in the *Uniform pricing* mode.

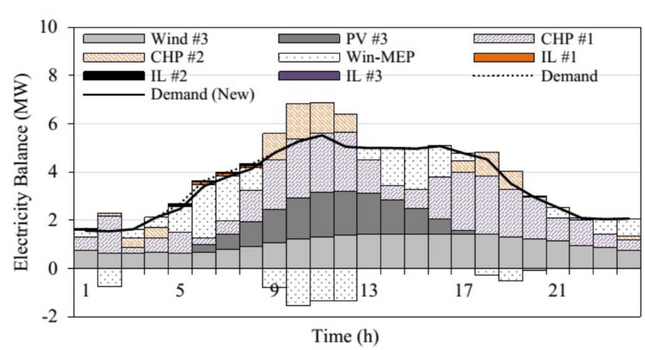

Fig. 4. Share of each element in the LES electricity balance in the *Uniform pricing* mode.

C. Effectiveness Assessment

The LES have two outputs to the MED. Therefore, the *LRUF* index has been calculated for both heat and electricity. Table II shows the amount of the system effectiveness indices for the two energy interaction modes. In the *Centralised management* mode, the MEP can control all facilities of LES directly, and can change the LES behaviour based on its willingness. Passing from the *Centralised management* mode to *Uniform pricing*, *LRUF* for heat has 11% increase, and for electricity 34% increase. As a matter of the fact, increasing the degree of freedom for decision making of LES results in more flexibility of LES to utilise their internal energy resources for both electricity and heat. The sharp increase in $LRUF_h$ is due to more utilisation of CHP and HS units in *Uniform pricing* mode compared with the *Centralised management* mode. Fig. 5 depicts the operational behaviour of HS during 24 hours, showing the different solution arising from the *Uniform pricing* mode.

TABLE II. EFFECTIVENESS INDICES

Mode	$LRUF_e$	$LRUF_h$
I – Centralised management	0.272	0.254
II – Uniform pricing	0.302	0.342

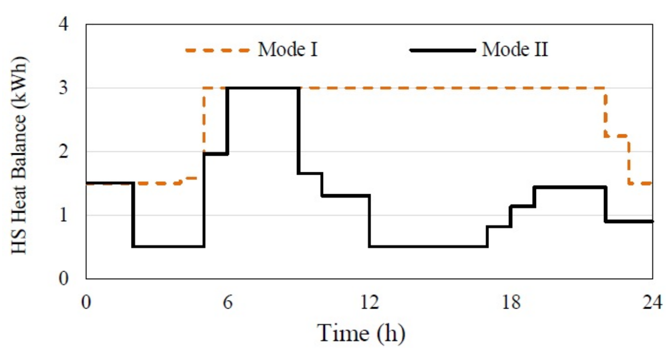

Fig. 5. Comparison of HS operation for the *Centralised management* and *Uniform pricing* modes.

VI. CONCLUSIONS

In this paper the MEP and LES decision-making conflict has been modelled through an MINLP bi-level approach. In the first level, the MEP aims to maximise its profit and the equilibrium prices are determined by cooperation of all LES. In the lower level, each LES schedules its energy balance based on the equilibrium price, and the energy exchange for each player will be concluded. For transforming the problem into a MILP single level problem, firstly the lower level problem has been replaced by its KKT optimality conditions. After that, based on the strong duality theorem, the objective function of the upper level problem has been linearized. Moreover, a dedicated index has been proposed to assess the effectiveness of decision-making frameworks in MES. The numerical results showed that the resource allocation of each LES determines its operational flexibility in short term and can explain its behaviour to cooperate with other LES in a MES. Moreover, providing appropriate energy interaction condition in a MES affected the MEP behaviour and released hidden synergy among LES. For local energy carriers that produce and consume locally (i.e., heat), the variable marginal price motivated the MEP to utilise its internal resources for maximising its profit. On the other hand, the main energy carriers that cannot be generated locally (i.e., gas) should be regulated appropriately to mitigate the market power of the upper level energy player.

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