This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/TSTE.2017.2701836, IEEE Transactions on Sustainable Energy

Aggregation of Distributed Energy Resources under the Concept of Multi-Energy Players in Local Energy Systems

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***Abstract*—In recent years, in addition to the traditional aspects concerning efficiency and profitability, the energy sector is facing new challenges given by environmental issues, security of supply, and the increasing role of the local demand. Therefore, the researchers have developed new decision-making frameworks enabling higher local integration of distributed energy resources (DER). In this context, new energy players appeared in the retail markets, increasing the level of competition on the demand side. In this paper, a multi-energy player (MEP) is defined, which behaves as a DER aggregator between the wholesale energy market and a number of local energy systems (LES). The MEP and the LES have to find a long-term equilibrium in the multi-energy retail market, in which they are interrelated through the price signals. To achieve this goal, in this paper the decision-making conflict between the market players is represented through a bi-level model, in which the decision variables of the MEP at the upper level are parameters for the decision-making problem at the lower level (for the individual LES). The problem is transformed into a mathematical program with equilibrium constraints by implementing duality theory, which is solved with the CPLEX 12 solver. The numerical results show the different MEP behavior in various conditions that impact on the total flexibility of the energy system.**

***Index Terms*—aggregation, bi-level model, decision-making, multi-energy, price signal.**

Nomenclature

A. Subscripts

e	Electricity
g	Natural gas
h	Heat
i	LES
n	Constraint
t	Time interval
ω	Set of scenarios

J.P.S. Catalão acknowledges the support of FEDER funds through COMPETE 2020 and Portuguese funds through FCT, under Projects FCOMP-01-0124-FEDER-020282 (Ref. PTDC/EEA-EEL/118519/2010), POCI-01-0145-FEDER-016434, POCI-01-0145-FEDER-006961, UID/EEA/50014/ 2013, UID/CEC/50021/2013, and UID/EMS/00151/2013, and also acknowledges funding from the EU Seventh Framework Programme FP7/2007-2013 under grant agreement no. 309048.

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B. Superscripts

AB	Auxiliary boiler
CHP	Combined heat and power
cha	Heat storage charging
$dcha$	Heat storage discharging
E	Equality constraints
EM	Electricity wholesale market
GM	Gas wholesale market
HS	Heat storage
IL	Interruptible load
in	Input energy to LES or HS
inc	The amount of load interruption incentivized
inj	Injected energy to MEP
LES	Local energy system
MEP	Multi-energy player
MED	Multi-energy demand
N	Non-equality constraints
out	Output energy from LES or HS
PV	Photovoltaic array
Sc	Scenario
$Wind$	Wind generation

C. Parameters

A	Number of energy storage units
B	Number of energy converters
I	Number of LES
G	Amount of natural gas supply
M^p, M^d	Very big parameters for the relaxation of the primal and dual constraints.
N	Number of constraints
Q	Amount of heat production
T	Time period
W	Amount of electricity generation
γ	Charge/discharge rate
ϕ	Heat to electricity ratio of CHP unit
ρ	Scenario probability
η	Efficiency
Π	Constant energy price
Ω	PV and wind scenarios

D. Variables

g	Amount of natural gas supply
q	Amount of heat production

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u	Binary variable
w	Amount of electricity generation
λ	Dual variables for equality constraints
$\underline{\mu}, \overline{\mu}$	Dual variables for the lower and upper limits of non-equality constraints.
ξ	Dual variables for equality constraints in specific time intervals.
π	Variable energy price

E. Vectors and matrices

$\mathbf{b}$	Vector of constant right hand-side of constraints.
$\mathbf{c}$	Vector of coefficients for the linear problem.
$\mathbf{e}$	Vector of equality constraints.
$\mathbf{n}$	Vector of non-equality constraints.
$\mathbf{t}$	Vector of equality constraints at specific time.
$\mathbf{x}$	Vector of decision variables.
$\boldsymbol{\psi}$	Vector of decision variables for dual problem.
$\boldsymbol{\lambda}$	Vector of dual variables for equality constraints
$\boldsymbol{\mu}$	Vector of dual variables for the non-equality constraints.
$\boldsymbol{\xi}$	Vector of dual variables for equality constraints in specific time intervals.
$\mathbf{H}$	Matrix of decision variables coefficients.

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

Remark II: Hat represents the expected value of variables.

I. Introduction

A. Motivation and Aims

THE penetration of distributed energy resources (DER), including distributed generation, demand response and distributed storage, is progressively increasing. Among the main drivers, together with energy efficiency and profitability, the current DER evolution depends on high DER impacts on environmental issues and security of supply, as well as economic opportunities for demand side stakeholders. The generation mix is changing at the supply side, to deliver the required energy demand. Meanwhile, the load mix changes, also by increasing the number of redundant appliances that deliver the same service being supplied through different energy carriers. The above-mentioned points raise the level of dependency among energy carriers [1] and give further opportunities to provide flexibility of usage of different energy carriers depending on the decisions undertaken by the end users in different time periods. Multi-energy systems and multi-energy arbitrage have been introduced to cope with such interdependent environment with increased flexibility due to the presence of multi-energy carriers [2].

The terminology used in this paper considers Local Energy Systems (LES) that convert and store a set of energy carriers to deliver the energy required to serve the multi-energy demand (MED). Fig. 1 depicts the role of multi-energy players (MEP) in the supply chain of the multi-energy system. The MEP is an energy player who aggregates a set of LES to maximize its operational profit and minimize its risk of participating in the energy markets, e.g., electricity and gas markets [3]. Aggregating the small scale LES at the demand side introduces a huge amount of flexible resources to the energy markets. This flexibility is helpful to decrease short and long run operation costs of the multi-energy system [4].

The MEP transactions with the LES involve more than one energy carrier. Therefore, the MEP behavior is different from the behavior of conventional energy players that trade just one energy carrier. The presence of more than one energy carrier motivates the MEP to exploit the inner LES flexibility and become in turn a flexible resource in the wholesale energy market.

B. Literature Review

The multi-energy concepts and models have been presented in various references, among which the energy hub model [5] and the matrix modeling for integrated representation of multi-energy systems [6]. These models represent some operation centers and their interconnectors. The operation centers deliver the required output services by converting and storing the input energy carriers [7]. The interconnectors are corridors that transmit the energy carriers from one operation center to other ones.

There are two main approaches for studying the various issues regarding the above-mentioned models:

- The first approach is to study a single operation center with the specific equipment;
- The second approach considers the management of a set of operation centers and their interconnectors.

Concerning the first approach, there is a variety of equipment that may be introduced, and whose presence impacts on the operational framework to be analyzed. In most of the existing models, the energy outputs of the operation centers are assumed as constant values or time series. However, in another view, the ultimate *service* provided to the end-users can be considered as the real requirement of the system to be provided with different input energy carriers. Therefore, instead of considering the energy vectors to be the output of the model, the required services are assumed as the new outputs. The specific focus on the services depends on the

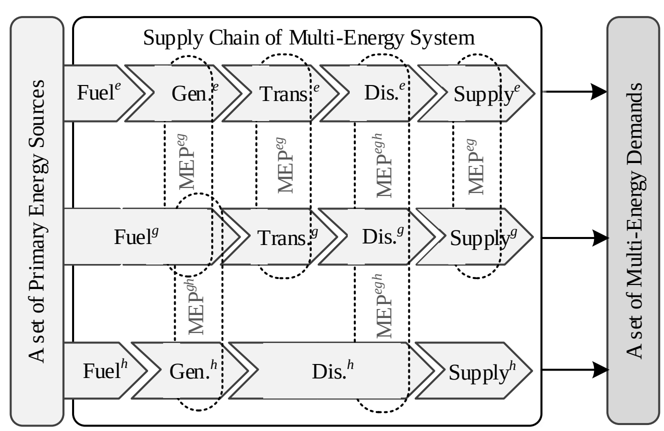

Fig. 1: Supply chain of energy system from primary resources to end-user.

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consumers availability of different energy carriers to obtain the same service. This ability can be considered as a particular type of provision of demand response resources from the upstream network point of view [8]. Moreover, the demand side management is modeled in [9] as an output of the energy hub, and the demand shifting is modeled in [10] to procure reserve services for electricity. The integration of renewable energy resources changes the interaction in the energy hub, as the renewable energy production can be injected into the network as well as being used at the local level. Hence, in [11] the energy hub model has been modified by adding a link to show the injection of the surplus energy from the energy hub output to the upstream network. Further applications have been presented in [12], with an operational framework for residential energy hub equipped with various end-use appliances and photovoltaic (PV) arrays, and in [13], where the energy storage has been modeled and its impacts in the planning time horizon have been investigated from both the utility and the household points of view.

With reference to the second approach, an integrated optimal power flow for gas and electricity networks has been proposed in [14]. The solution procedure has been developed in [15] and a multi-agent genetic algorithm has been used to cope with the large-scale non-linear problem, decreasing the computation time and increasing the accuracy of the results. A decentralized control framework for modeling the cooperative environment of energy hubs has been presented in [16]. The amount of energy exchanged and the marginal cost of energy production are considered as coupling signals among the energy hubs. In other works such as [17] a framework for retail electricity market has been introduced, proposing a model for integration of electricity prosumers. In addition, also [18] refers to electricity as the only energy carrier considered in the operation of multimicrogrids.

Although in some other works such as [17] a framework for retail energy market has been introduced, it should be noted that the study in [17] only considers the electricity market and proposes the model for integration of electricity prosumers in the retail market. In the current work the introduced MEP benefits from the integration of different energy carriers (e.g., electricity, gas, district heating) and the decision-making procedure is based on the possibility of energy shifting between different energy carriers. Consequently, this will make the present study different from other contributions. For example, the main concept in [18] is based on the microgrid operation of the energy systems, also validated in a test bed [20], with electricity as the only energy carrier, while the framework proposed in the current study can be further employed in a multi-energy environment in different operation modes. The same reasoning explains the differences of the current work with respect to what has been presented in [19].

C. Contributions

The main contributions of this paper are as follows:

- The introduction of the MEP as a multi-commodity energy player. Several LES are considered, and the presence of the MEP increases the efficiency of integrating different energy carriers (e.g., electricity, gas, and heat).
- The proposal of an aggregation approach for MEP at the distribution level, coupling the LES on the basis of an equilibrium energy price signal.
- The proposal of an index to assess the effectiveness of the aggregation approach at the energy distribution level.

In particular, with respect to [16], the proposed model is targeted for an energy market in which the coupling signals are the energy prices, rather than using the marginal cost of energy production. With respect to [18], the proposed decision-making procedure is based on the possibility of shifting energy between different carriers, rather than considering electricity as the sole energy carrier.

The focus of the proposed approach is set on addressing the interactions of the various multi-energy system components in a comprehensive market model through the introduction of MEP. The LES input and output are restricted inside the capacity limits of the interconnectors. The distribution network is not explicitly represented, namely, the energy networks are introduced with the single-node model, assuming no congestion occurs in the energy networks .

D. Paper Organization

The rest of paper is organized as follows. Section II describes the problem and introduces the objective functions and constraints for the various entities operating in the multi-energy system. In Section III the energy and price exchanges among MEP and LES are represented on the basis of a bi-level model. Section IV introduces an effectiveness indicator representing the LES capability of using internal resources rather than taking energy from the supply systems for each energy carrier, and describes different types of LES management. Section V illustrates and discusses the numerical results obtained in some case study applications, quantifying the results of the multi-energy system operation. The last section contains the concluding remarks.

II. Definition and Mathematical Formulation of the MEP Interacting with the LES

A. Problem Description

This paper proposes a hierarchical optimization tool to model the interactions among the MEP and a set of LES. Fig. 2 shows the comprehensive view of the decision making procedure, organized into four layers, namely, the wholesale energy markets, the MEP, the LES, and the MED [21]. In particular:

- In the wholesale energy market layer, different energy players compete with each other, and the main goal of the independent market operator is to maximize the social welfare.
- The MEP behaves as an energy aggregator that facilitates energy and financial interactions between LES and the upstream wholesale energy markets. In this layer, the goal is the maximization of the MEP profit.
- The LES contain DER and exchange the energy carriers used to supply the MED (e.g., electricity, gas, and heat) with other LES and the MEP. The specific objective is the maximization of the LES profit.

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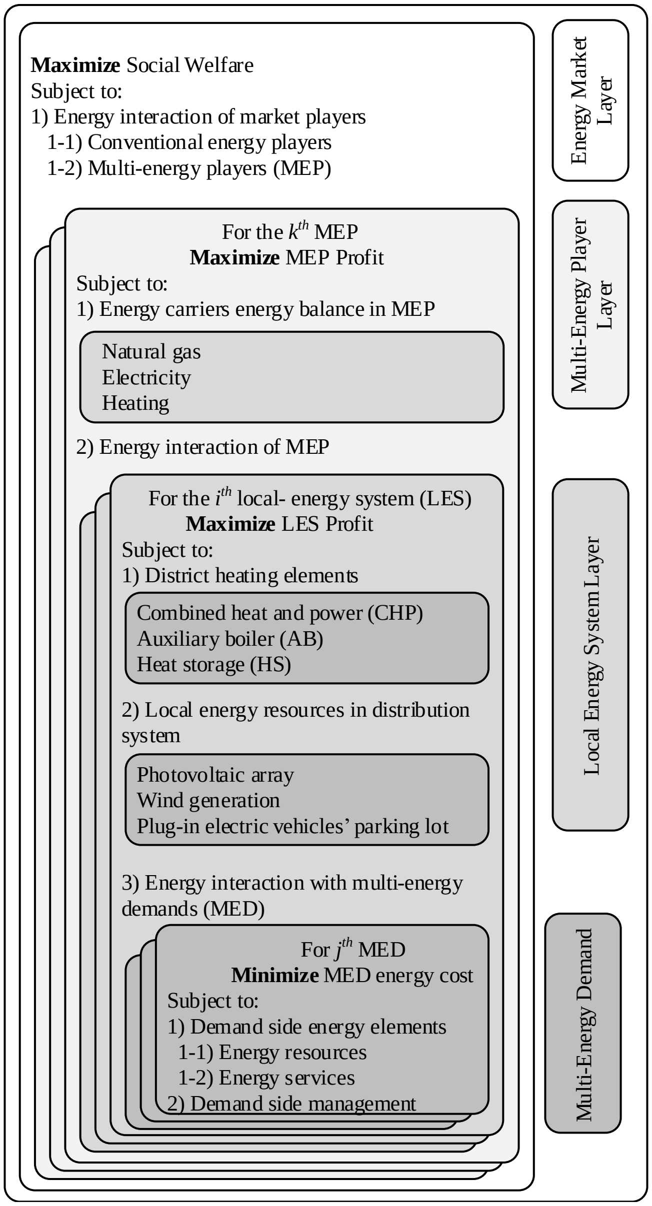

Fig. 2: Hierarchical structure of the decision-making procedure.

- In the MED layer, the objective is the minimization of the MED energy costs.

To address these issues, a hierarchical bi-level model has been introduced to represent the behavior of MEP and LES in the multi-energy system. This type of model is generally adopted when the decisions undertaken by a leader at the upper level affect the decisions to be taken by the followers at the lower level, while the decision of the followers have an impact on the leaders decisions as well. The relevant aspect is the time sequence, that is, the leader decides prior to the followers. However, the leader needs to get a feedback on how its decisions may change the decisions of the followers. In the bi-level model (representing a Stackelberg game [22]) the decision variables used by the leader at the upper level become parameters for the problem solves at the lower level.

In the formulation presented in this paper, at the upper level, the MEP maximizes its profit while satisfying the LES energy exchange. The coupling variables among MEP and LES are the energy prices determined on the basis of the MEP strategic behavior at the energy distribution level. Then, at the lower level each LES schedules its energy balance of operation center based on the first level price signal and determines the quantity of exchanged energy. The problem is transformed into a mathematical program with equilibrium constraints (MPEC), solved with the CPLEX 12 solver through the GAMS software.

Fig. 3 indicates more details of the MEP interaction with LES and wholesale energy markets. The MEP trades energy (i.e., electricity and gas) in the energy market with predetermined price signals, and manages the energy exchange (i.e., electricity, gas, and heat) among its LES. Therefore, the decision making vector of MEP contains the entries $[\pi_{e,t}^{MEP}, \pi_{g,t}^{MEP}, \pi_{h,t}^{MEP}, w_t^{MEP}, g_t^{MEP}]$.

On the other hand, each LES exchanges energy (i.e., electricity, gas, and heat) to serve the MED with time of use (TOU) prices, and exchanges energy at the LES level with a competitive price. In the proposed bi-level model the decision-making vector of the LES contains the entries $[\hat{w}_{i,t}^{LES,in}, \hat{w}_{i,t}^{LES,out}, \hat{q}_{i,t}^{LES,in}, \hat{q}_{i,t}^{LES,out}, \hat{g}_{i,t}^{LES}]$. As a matter of fact, gas and electricity are the main energy carriers traded at all levels, while heat is a local energy carrier that is only exchanged at the LES level.

B. Multi-Energy Player level

1) Objective Function: The MEP aggregates the energy trade of LES and manages the energy exchange among them. The objective of MEP is maximizing its profit resulting from the energy exchange with its LES and the energy market. It is assumed that the share of MEP from the wholesale energy market is negligible, therefore the operator is considered as a price taker in the energy market and trades energy (i.e., gas and electricity) at predetermined prices ($\Pi_{e,t}^{MEP}$ and $\Pi_{g,t}^{MEP}$). On the other hand, the MEP determines the coupling price among LES. Moreover, the LES contain uncertain energy resources and their energy quantity is indicated based on their internal

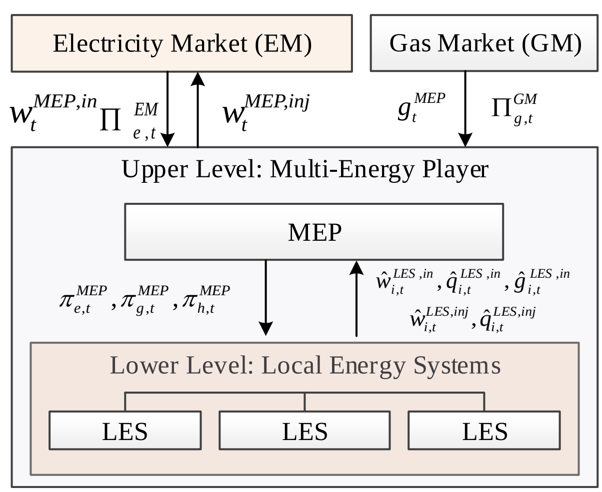

Fig. 3: Interaction of MEP with LES and the wholesale electricity market.

uncertainty characterization. To achieve this goal a stochastic model is developed to consider the uncertain behavior of PV and wind resources through a set of scenarios. The scenario generation procedure is presented in Appendix A [23]. On the other hand, at the MEP level there is no source of uncertainty and the LES participate with their expected values of energy exchange in the MEP aggregation environment. The equations (1)-(6) represent the operational problem for the MEP and are based on references [1] and [21].

The objective function for the MEP is expressed as follows:

$$\max\left\{\sum_t\left[-\left(w_t^{MEP}\Pi_{e,t}^{EM}+g_t^{MEP}\Pi_{g,t}^{GM}\right)\right.\right.$$
$$\left.\left.+\sum_i\left(\hat{w}_{i,t}^{LES}\pi_{e,i,t}^{MEP}+\hat{g}_{i,t}^{LES}\pi_{g,i,t}^{MEP}+\hat{q}_{i,t}^{LES}\pi_{h,i,t}^{MEP}\right)\right]\right\} \quad (1)$$

2) Constraints: The main constraints of MEP deals with its energy contract and economical restrictions that appear in energy exchange limits.

Input energy limitation: the energy exchanged by the MEP with the energy market is limited to predetermined energy exchange limits

$$\underline{W}^{MEP} \leq w_t^{MEP} \leq \overline{W}^{MEP} \quad (2)$$
$$0 \leq g_t^{MEP} \leq \overline{G}^{MEP} \quad (3)$$

MEP energy balance: In the literature the energy interactions between LES are represented by using linear and non-linear models. In the linear models the voltage and pressure drop between LES are neglected and the model is considered based on linear energy balance equations for each network node. Reference [24] proposed a nonlinear model for both gas and electricity energy carriers considering AC load flow for electricity and pressure-based model for gas network. Moreover, Ref. [25] considered a linear model for energy interaction between LES based on the energy balance equations for each node.

In this paper, the energy network is considered as a single node and the energy interactions between LES are based on linear energy balance equations for the three energy carriers. Equations (4)-(6) indicate the energy balance in the MEP for electricity, gas, and heat, respectively. The heat is a local energy carrier and its energy balance is based on the energy exchange among LES only, while the electricity and gas energy balance should be determined based on both energy exchanges with the energy market and the LES.

$$w_t^{MEP}-\sum_i \hat{w}_{i,t}^{LES}=0 \quad (4)$$
$$g_t^{MEP}-\sum_i \hat{g}_{i,t}^{LES}=0 \quad (5)$$
$$\sum_i \hat{q}_{i,t}^{LES}=0 \quad (6)$$

C. Local Energy System Level

Equation (7) presents the general form of the optimization problem for the LES. Given the vector $\mathbf{x}_i$ containing the decision variables for the i^{th} LES, $f_i(\mathbf{x}_i)$ is the objective function used for the LES optimization based on the LES internal energy schedule and on the energy exchange at the MEP level, where $\mathbf{e}_i(\mathbf{x}_i)$ and $\mathbf{n}_i(\mathbf{x}_i)$ are vectors of equality and inequality constraints, respectively.

$$\begin{gathered}\min\{f_i(\mathbf{x}_i)\}\\ \text{Subject to :}\\ \mathbf{e}_i(\mathbf{x}_i)=\mathbf{0}\\ \mathbf{n}_i(\mathbf{x}_i)\geqslant\mathbf{0}\\ \mathbf{x}_i\geqslant\mathbf{0}\end{gathered} \quad (7)$$

1) Objective Function: The objective of LES is maximizing its profit (implemented as minimizing the minus-profit [30]) from selling energy to the MED and trading energy with the MEP, while meeting the operational constraints of its internal energy elements. Equations (8)-(11) describe the expected values of LES energy exchange with the MEP.

$$f_i(\mathbf{x}_i)=\sum_t\left[\left(\hat{w}_{i,t}^{LES}\pi_{e,i,t}^{MEP}+\hat{g}_{i,t}^{LES}\pi_{g,i,t}^{MEP}+\right.\right.$$
$$\left.\hat{q}_{i,t}^{LES}\pi_{h,i,t}^{MEP}\right)-\left(\left(W_{i,t}^{MED}-w_{i,t}^{IL}\right)\Pi_{e,i,t}^{MED}+G_{i,t}^{MED}\Pi_{g,i,t}^{MED}\right.$$
$$\left.\left.+Q_{i,t}^{MED}\Pi_{h,i,t}^{MED}-w_{i,t}^{IL}\Pi_{i,t}^{IL,inc}\right)\right] \quad (8)$$

with

$$\hat{w}_{i,t}^{LES}=\sum_\omega \rho_\omega\left(w_{i,\omega,t}^{LES,in}-w_{i,\omega,t}^{LES,inj}\right) \quad (9)$$
$$\hat{q}_{i,t}^{LES}=\sum_\omega \rho_\omega\left(q_{i,\omega,t}^{LES,in}-q_{i,\omega,t}^{LES,inj}\right) \quad (10)$$
$$\hat{g}_{i,t}^{LES}=\sum_\omega \rho_\omega g_{i,\omega,t}^{LES} \quad (11)$$

2) Constraints: Equations (12)-(14) contain the energy balance for gas, heat, and electricity, respectively, in the LES. These balances are based on the internal energy exchange of the specific energy components included in the LES, e.g., combined heat and power (CHP), auxiliary boiler (AB), heat storage (HS), and interruptible load (IL). Moreover, the dual variables of each constraint are indicated after the right hand side of the respective equation.

$$E_{i,\omega,t}^{LES,1}: W_{i,t}^{MED}-w_{i,\omega,t}^{LES,in}\eta_{e,i}^{Trans}+w_{i,\omega,t}^{LES,inj}/\eta_{e,i}^{Trans}$$
$$-w_{i,\omega,t}^{Wind}-w_{i,\omega,t}^{PV}-w_{i,\omega,t}^{IL}-w_{i,\omega,t}^{CHP}=0$$
$$:\lambda_{e,i,\omega,t}^{MED},\forall i,\forall t,\forall\omega \quad (12)$$

$$E_{i,\omega,t}^{LES,2}: G_{i,t}^{MED}-g_{i,\omega,t}^{LES}+g_{i,\omega,t}^{CHP}+g_{i,\omega,t}^{AB}$$
$$:\lambda_{g,i,\omega,t}^{MED},\forall i,\forall t,\forall\omega \quad (13)$$

$$E_{i,\omega,t}^{LES,3}: Q_{i,t}^{MED} - q_{i,\omega,t}^{LES,in}\eta_{h,i}^{LES} + q_{i,\omega,t}^{LES,out}/\eta_{h,i}^{LES} + q_{i,\omega,t}^{HS,in} - q_{i,\omega,t}^{HS,out} - q_{i,\omega,t}^{CHP} - q_{i,\omega,t}^{AB} = 0 \quad : \lambda_{h,i,\omega,t}^{MED}, \forall i, \forall t, \forall \omega \tag{14}$$

Input energy limitation: The LES input and output energy are restricted by the interconnectors capacity as follows:

$$N_{i,\omega,t}^{LES,1}, N_{i,\omega,t}^{LES,2}: 0 \leq w_{i,\omega,t}^{LES,in} \leq \overline{W}_i^{LES} \quad : \underline{\mu}_{e,i,\omega,t}^{LES,in}, \overline{\mu}_{e,i,\omega,t}^{LES,in}, \forall i, \forall t, \forall \omega \tag{15}$$

$$N_{i,\omega,t}^{LES,3}, N_{i,\omega,t}^{LES,4}: 0 \leq w_{i,\omega,t}^{LES,out} \leq \overline{W}_i^{LES} \quad : \underline{\mu}_{e,i,\omega,t}^{LES,out}, \overline{\mu}_{e,i,\omega,t}^{LES,out}, \forall i, \forall t, \forall \omega \tag{16}$$

$$N_{i,\omega,t}^{LES,5}, N_{i,\omega,t}^{LES,6}: 0 \leq q_{i,\omega,t}^{LES,in} \leq \overline{Q}_i^{LES} \quad : \underline{\mu}_{h,i,\omega,t}^{LES,in}, \overline{\mu}_{h,i,\omega,t}^{LES,in}, \forall i, \forall t, \forall \omega \tag{17}$$

$$N_{i,\omega,t}^{LES,7}, N_{i,\omega,t}^{LES,8}: 0 \leq q_{i,\omega,t}^{LES,out} \leq \overline{Q}_i^{LES} \quad : \underline{\mu}_{h,i,\omega,t}^{LES,out}, \overline{\mu}_{h,i,\omega,t}^{LES,out}, \forall i, \forall t, \forall \omega \tag{18}$$

$$N_{i,\omega,t}^{LES,9}, N_{i,\omega,t}^{LES,10}: 0 \leq g_{i,\omega,t}^{LES} \leq \overline{G}_i^{LES} \quad : \underline{\mu}_{g,i,\omega,t}^{LES}, \overline{\mu}_{g,i,\omega,t}^{LES}, \forall i, \forall t, \forall \omega \tag{19}$$

CHP operational constraints: The CHP unit consumes gas and generates electricity and heat ((20) and (21)). Moreover, the amount of the heat and electricity production are restricted based on characteristics ((22)-(24)) of the unit, while its heat to electricity ratio (Φ_i^{CHP}) is a constant value.

$$E_{i,\omega,t}^{LES,4}: w_{i,\omega,t}^{CHP} - \eta_{e,i}^{CHP} g_{i,\omega,t}^{CHP} = 0 \quad : \lambda_{e,i,\omega,t}^{CHP}, \forall i, \forall t, \forall \omega \tag{20}$$

$$E_{i,\omega,t}^{LES,5}: q_{i,\omega,t}^{CHP} - \eta_{h,i}^{CHP} g_{i,\omega,t}^{CHP} = 0 \quad : \lambda_{h,i,\omega,t}^{CHP}, \forall i, \forall t, \forall \omega \tag{21}$$

$$N_{i,\omega,t}^{LES,11}, N_{i,\omega,t}^{LES,12}: 0 \leq w_{i,\omega,t}^{CHP} \leq \overline{W}_i^{CHP} \quad : \underline{\mu}_{e,i,\omega,t}^{CHP}, \overline{\mu}_{e,i,\omega,t}^{CHP}, \forall i, \forall t, \forall \omega \tag{22}$$

$$N_{i,\omega,t}^{LES,13}, N_{i,\omega,t}^{LES,14}: 0 \leq q_{i,\omega,t}^{CHP} \leq \overline{Q}_i^{CHP} \quad : \underline{\mu}_{h,i,\omega,t}^{CHP}, \overline{\mu}_{h,i,\omega,t}^{CHP}, \forall i, \forall t, \forall \omega \tag{23}$$

$$E_{i,\omega,t}^{LES,6}: w_{i,\omega,t}^{CHP}\Phi_i^{CHP} - q_{i,\omega,t}^{CHP} = 0 \quad : \lambda_{i,\omega,t}^{Ratio}, \forall i, \forall t, \forall \omega \tag{24}$$

AB operational constraints: The output heat of the AB is related to its efficiency and should be lower than its maximum capacity.

$$E_{i,\omega,t}^{LES,7}: q_{i,\omega,t}^{AB} - \eta_{e,i}^{AB} g_{i,\omega,t}^{AB} = 0 \quad : \lambda_{h,i,\omega,t}^{AB}, \forall i, \forall t, \forall \omega \tag{25}$$

$$N_{i,\omega,t}^{LES,15}, N_{i,\omega,t}^{LES,16}: 0 \leq q_{i,\omega,t}^{AB} \leq \overline{Q}_i^{AB} \quad : \underline{\mu}_{h,i,\omega,t}^{AB}, \overline{\mu}_{h,i,\omega,t}^{AB}, \forall i, \forall t, \forall \omega \tag{26}$$

HS operational constraints: The stored heat at each hour is related to the energy exchange of the HS with the LES and should be lower than the HS limitations. Moreover, for consistency in the study period, the amount of the stored energy at the starting and ending hours of the period are considered to be equal and are set to one half of the maximum capacity.

$$E_{i,\omega,t}^{LES,8}: Q_{i,\omega,t}^{HS} - q_{i,\omega,t-1}^{HS}\Big|_{t>1} - 0.5Q_{i,\omega,t}^{HS}\Big|_{t=1} + q_{i,\omega,t}^{HS,in}\eta_{h,i}^{HS} - q_{i,\omega,t}^{HS,out}/\eta_{h,i}^{HS} = 0 \quad : \lambda_{h,i,\omega,t}^{HS}, \forall i, \forall t, \forall \omega \tag{27}$$

$$N_{i,\omega,t}^{LES,17}, N_{i,\omega,t}^{LES,18}: 0 \leq q_{i,\omega,t}^{HS,in} \leq \gamma_i^{HS} \quad : \underline{\mu}_{h,i,\omega,t}^{HS,in}, \overline{\mu}_{h,i,\omega,t}^{HS,in}, \forall i, \forall t, \forall \omega \tag{28}$$

$$N_{i,\omega,t}^{LES,19}, N_{i,\omega,t}^{LES,20}: 0 \leq q_{i,\omega,t}^{HS,out} \leq \gamma_i^{HS} \quad : \underline{\mu}_{h,i,\omega,t}^{HS,out}, \overline{\mu}_{h,i,\omega,t}^{HS,out}, \forall i, \forall t, \forall \omega \tag{29}$$

$$N_{i,\omega,t}^{LES,21}, N_{i,\omega,t}^{LES,22}: 0 \leq q_{i,\omega,t}^{HS} \leq \overline{Q}_i^{HS} \quad : \underline{\mu}_{h,i,\omega,t}^{HS}, \overline{\mu}_{h,i,\omega,t}^{HS}, \forall i, \forall t, \forall \omega \tag{30}$$

$$T_{i,\omega,t}^{LES,1}: q_{i,\omega,t=1}^{HS} = \overline{Q}_{i,\omega}^{HS}/2 + q_{i,\omega,t=1}^{HS,in}\eta_{h,i}^{HS} - q_{i,\omega,t=1}^{HS,out}/\eta_{h,i}^{HS} = 0 \quad : \xi_{h,i,\omega,t=1}^{HS}, \forall i, t=1, \forall \omega \tag{31}$$

$$T_{i,\omega,t}^{LES,2}: q_{i,\omega,t=T}^{HS} = \overline{Q}_{i,\omega}^{HS}/2 + q_{i,\omega,t=T}^{HS,in}\eta_{h,i}^{HS} - q_{i,\omega,t=T}^{HS,out}/\eta_{h,i}^{HS} = 0 \quad : \xi_{h,i,\omega,t=T}^{HS}, \forall i, t=T, \forall \omega \tag{32}$$

PV arrays operational constraint: Some scenarios are implemented to model the uncertain nature of the PV array generation. The generation in each hour should be based on the scenario amounts.

$$N_{i,\omega,t}^{LES,23}, N_{i,\omega,t}^{LES,24}: 0 \leq w_{i,\omega,t}^{PV} \leq \overline{W}_i^{PV,Forecast} \quad : \underline{\mu}_{e,i,\omega,t}^{PV}, \overline{\mu}_{e,i,\omega,t}^{PV}, \forall i, \forall t, \forall \omega \tag{33}$$

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Wind generation operational constraint: Similar to PV array, for wind generation, the output energy is based on the wind scenarios.

$$N_{i,\omega,t}^{LES,25}, N_{i,\omega,t}^{LES,26} : 0 \leq w_{i,\omega,t}^{Wind} \leq \overline{W}_{i}^{Wind,Forecast} \\ : \underline{\mu}_{e,i,\omega,t}^{Wind}, \overline{\mu}_{e,i,\omega,t}^{Wind}, \forall i, \forall t, \forall \omega \quad (34)$$

Interruptible load: The LES operator gives an incentive to the MED to reduce its consumption while the input energy price is high and the energy production is not profitable for the LES. In this paper the IL is only considered for electricity and $\alpha_{i,t}^{IL}$ is the percentage of electrical demand that can be interrupted.

$$N_{i,\omega,t}^{LES,27}, N_{i,\omega,t}^{LES,28} : 0 \leq w_{i,\omega,t}^{IL} \leq \alpha_{i,t}^{IL} W_{i,t}^{MED} \\ : \underline{\mu}_{e,i,\omega,t}^{IL}, \overline{\mu}_{e,i,\omega,t}^{IL}, \forall i, \forall t, \forall \omega \quad (35)$$

III. Mathematical Formulation of the MEP and LES Decision Making Conflict

Based on the proposed formulation, MEP and LES are active in two different levels. The model can be considered as a Stackelberg game in which at the upper level there is the MEP as a leader, and at the lower level there are LES as followers. The MEP determines the energy price, and the LES schedule their internal energy resources and propose their energy exchange based on the price signals. Due to the terms $\hat{w}_{i,t}^{LES}\pi_{e,i,t}^{MEP}$, $\hat{g}_{i,t}^{LES}\pi_{g,i,t}^{MEP}$, and $\hat{q}_{i,t}^{LES}\pi_{h,i,t}^{MEP}$ in the objective function the lower level problem is non-linear. To linearize these terms, the upper level price signal is considered as an input parameter for the lower level problem. Therefore, the lower level problems can be replaced by their Karush-Kuhn-Tucker (KKT) optimality conditions. After that, the strong duality theorem enforces to the problem to linearize the non-linear terms of the upper level objective function (i.e. $\hat{w}_{i,t}^{LES}\pi_{e,i,t}^{MEP}$, $\hat{g}_{i,t}^{LES}\pi_{g,i,t}^{MEP}$, and $\hat{q}_{i,t}^{LES}\pi_{h,i,t}^{MEP}$) [22], [26]. Therefore, the bi-level problem is transformed into a single level MILP problem.

A. Problem Formulation at the LES Level

As explained before, the lower level equations (12)-(35) are linear and thus convex. For replacing the lower level problem with its KKT optimality conditions, the Lagrangian expression of the lower level problem is determined as in (36), where $\boldsymbol{\mu}_i$, $\boldsymbol{\lambda}_i$, and $\boldsymbol{\xi}_i$ are dual variables of LES inequality constraints, equality constraints, and equality constraints in specific time intervals, respectively. Equations (37)-(40) represent the KKT conditions of the lower level problem. Equation (37) is the stationarity condition, equations (38) and (39) are primal feasibility conditions, and (40) is the complementarity condition of the KKT optimality conditions. The superscript T denotes transposition.

$$\mathcal{L}_i = f_i(\mathbf{x}_i) - \boldsymbol{\mu}_i^{\mathrm{T}}\mathbf{n}_i(\mathbf{x}_i) + \boldsymbol{\lambda}_i^{\mathrm{T}}\mathbf{e}_i(\mathbf{x}_i) + \boldsymbol{\xi}_i^{\mathrm{T}}\mathbf{t}_i(\mathbf{x}_i) \quad (36)$$

$$\partial\mathcal{L}_i/\partial\mathbf{x}_i = \mathbf{0} \quad (37)$$

$$\partial\mathcal{L}_i/\partial\boldsymbol{\lambda}_i = \mathbf{e}_i(\mathbf{x}_i) = \mathbf{0} \quad (38)$$

$$\partial\mathcal{L}_i/\partial\boldsymbol{\xi}_i = \mathbf{t}_i(\mathbf{x}_i) = \mathbf{0} \quad (39)$$

$$\mathbf{0} \leqslant \boldsymbol{\mu}_i \perp \mathbf{n}_i(\mathbf{x}_i) \geqslant \mathbf{0} \quad (40)$$

For linearizing the complementarity condition, a set of binary variables ($\mathbf{u}_i$) are introduced to transform the equation (40) into the equations (41) and (42) [22]. The parameter M is used to relax the complementary condition, and should be calculated on the basis of the range of variation of the variables appearing in the problem. For the primal problem, the range of variation of its variables is based on the energy scale. For the dual problem, the range of variation of its variables is based on the energy price scale. It is possible to determine a specific M for each equation, but for the sake of simplicity two values are considered, M^p for the primal problem, and M^d for the dual problem; each of them is based on the maximum range of variation that occurs for the variables of the corresponding problem.

$$\mathbf{0} \leqslant \mathbf{n}_i(\mathbf{x}_i) \leqslant M^p \ \mathbf{u}_i \quad (41)$$

$$\mathbf{0} \leqslant \boldsymbol{\mu}_i \leqslant M^d \ \mathbf{u}_i \quad (42)$$

B. Linearizing the MEP Objective Function

Equation (43) is the primal optimization problem of the lower level problem that is formed. It is based on the decision variables $\mathbf{x}_i$, and on the matrix $\mathbf{H}_i$ and the column vector $\mathbf{b}_i$ derived from the equality and non-equality constraints, expressed as in Equation (44).

$$\begin{gathered} \min \ \{\mathbf{c}_i^{\mathrm{T}}\mathbf{x}_i\} \\ \text{Subject to}: \mathbf{H}_i\mathbf{x}_i - \mathbf{b}_i \geqslant \mathbf{0}, \\ \text{where } \mathbf{c}_i \text{ is the vector of coefficients} \\ \Rightarrow \begin{cases} \mathbf{e}_i(\mathbf{x}_i) : \mathbf{H}_i^E\mathbf{x}_i = \mathbf{0} \\ \mathbf{n}_i(\mathbf{x}_i) : \mathbf{H}_i^N\mathbf{x}_i - \mathbf{b}_i^N \geqslant \mathbf{0} \end{cases} \\ \mathbf{x}_i \geqslant \mathbf{0} \end{gathered} \quad (43)$$

$$\mathbf{H}_i = \begin{bmatrix} \mathbf{H}_i^E \\ \mathbf{H}_i^N \end{bmatrix}, \mathbf{b}_i = \begin{bmatrix} \mathbf{0} \\ \mathbf{b}_i^N \end{bmatrix} \quad (44)$$

Equation (45) shows the dual form of the lower level problem introduced in equation (43). The vector $\boldsymbol{\psi}_i$ contains the dual variables of the LES constraints, indicated in the last part of the equations (12)-(35).

$$\begin{gathered} \max \ \{\mathbf{b}_i^{\mathrm{t}}\boldsymbol{\psi}_i\} \\ \text{Subject to}: \mathbf{H}_i^{\mathrm{t}}\boldsymbol{\psi}_i - \mathbf{c}_i \leqslant \mathbf{0} \\ \boldsymbol{\psi}_i \geqslant \mathbf{0} \end{gathered} \quad (45)$$

Equation (46) illustrates the strong duality condition for the lower level problem. This condition states that, for linear (and thus convex) problems, the gap of the dual and primal objective functions can be considered as zero, so the objective functions of the primal and dual problems become equal [17].

The nonlinear terms of the MEP objective function ($\hat{w}_{i,t}^{LES}\pi_{e,i,t}^{MEP}$, $\hat{g}_{i,t}^{LES}\pi_{g,i,t}^{MEP}$, and $\hat{q}_{i,t}^{LES}\pi_{h,i,t}^{MEP}$) are the same as the non-linear terms of the objective function of the LES. Therefore, they can be replaced based on (46) by their linear forms, which are derived from the strong duality condition.

$$\mathbf{c}_i^{\mathrm{t}}\mathbf{x}_i = \mathbf{b}_i^{\mathrm{t}}\boldsymbol{\psi}_i \tag{46}$$

IV. System Effectiveness in Various Energy Interaction Conditions

A. System Effectiveness Index

The system effectiveness index considered is related to the capability of the LES to utilize their internal energy resources instead of importing energy from the upstream network. Equation (47) shows the general formulation to calculate this index for the generic energy carrier c that will be delivered to the MED. The effectiveness of the energy storage unit $\alpha = 1, ..., A$ to mitigate the variation of the system is considered as the variation of the normalized energy level of storage in consecutive time intervals (the first addend in equation (47)). For energy converters, the index is based on the share of the output energy to the maximum capacity of the energy converter $\beta = 1, ..., B$ in the study time horizon (the second addend in equation (47)).

$$LRUF_c = \frac{1}{T(A+B)} \left[\sum_{\alpha=1}^{A}\sum_{t=1}^{T}\frac{|E_{\alpha,c,t}-E_{\alpha,c,t-1}|}{\overline{E}_{\alpha,c}} + \sum_{\beta=1}^{B}\sum_{t=1}^{T}\frac{E_{\beta,c,t}}{\overline{E}_{\beta,c}}\right] \tag{47}$$

B. Energy Interaction Conditions

Three energy interaction conditions are considered in this paper for aggregation of LES by the MEP.

1) Centralized management for LES: In this aggregation mode, the MEP manages all the energy facilities of the LES. This mode is related to the capability of the MEP to have at least one-way communication with the 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. Equation (48) shows the objective function of MEP that operates the whole system by utilizing LES facilities and interacting with the energy market.

$$\max\left\{\sum_t -(w_t^{MEP}\Pi_{e,t}^{EM} + g_t^{MEP}\Pi_{g,t}^{GM})\right\} \tag{48}$$

2) Direct pricing for LES: In this mode, the MEP sends a specific price signal to each LES, and the LES send back their energy schedule to the MEP. Therefore, the MEP and each LES have an equilibrium price for each energy carrier. The difference between the LES prices helps the MEP interact energy with each LES independently. The mathematical model for the direct pricing scheme is represented by (1)-(35). In this model the energy price for each LES has i dimensions, as it is specified for each LES (i.e. $\pi_{e,i,t}^{MEP}$, $\pi_{g,i,t}^{MEP}$, and $\pi_{h,i,t}^{MEP}$).

3) Uniform pricing for LES: In this 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 same energy price is used for all LES (i.e. $\pi_{e,t}^{MEP}$, $\pi_{g,t}^{MEP}$, and $\pi_{h,t}^{MEP}$).

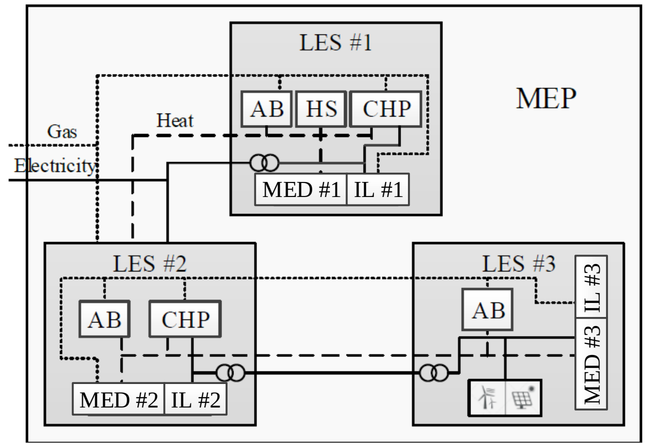

Fig. 4: MEP and LES cooperation environment schematic.

V. Numerical Results

A. Input Data Characterization

The numerical study is prepared to show the effectiveness of the proposed framework in real-life cases and track the behavior of the energy players. Without loss of generality, with the aim of providing a detailed view on the results, initially three LES are considered as the minimum possible amount of LES that can support the research idea (Fig. 4). In the proposed case study, each LES has a certain specification. LES #1 and #2 are CHP-based and generate both electricity and heat, simultaneously. LES #1 is also equipped with HS; therefore, it can substitute its heat energy consumption between time intervals. On the contrary, LES #3 is renewable energy-based and can generate cheap electricity, but the heat production marginal cost of this LES will be higher than other LES because it is not equipped with CHP and HS units.

It is assumed that the MEP is a price taker in the energy market. Therefore, its interaction with other energy players in the energy market is based on the predetermined energy carriers' price signals (Fig. 5). Data of electricity prices for the MEP input have been obtained from the hourly data of the Spanish electricity market in May 2015 [28].

The LES consist of CHP, AB, HS, IL, and renewable energy generation. The comprehensive data for elements of these three LES are represented in Table I. The MILP problem has been solved with the CPLEX12 solver under the license of the GAMS software, with an HP Z800 Workstation (CPU 3.47 GHz, RAM 96GB).

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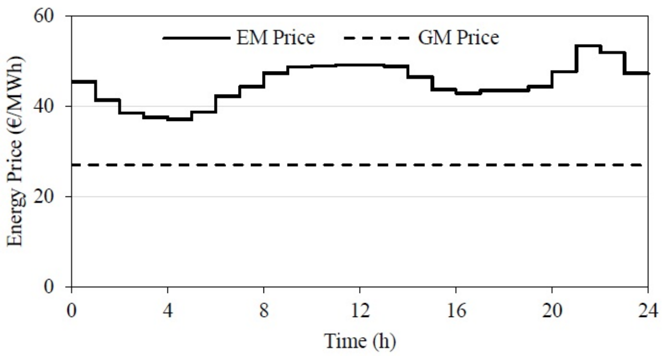

Fig. 5: The hourly price of electricity and gas markets.

TABLE I: DATA OF THE LOCAL ENERGY SYSTEM.

Elements		LES1	LES2	LES3
LES	Transformer	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	—
	η_e^{CHP}, η_h^{CHP}	0.43, 0.35	0.45, 0.3	—
AB	Heat Output	2 MW	3 MW	1.5 MW
	η_h^{AB}	0.9	0.85	0.9
HS	Energy Capacity	3 MWh	—	—
	γ_h^{HS}	1.5 MW	—	—
	$\eta_h^{HS,cha}$, $\eta_h^{HS,dcha}$	0.9, 0.81	—	—
Renewable	Wind Capacity	—	—	3.3 MW
	PV Capacity	—	—	3.3 MW

B. Evaluation of Players' Energy Interaction Behavior

1) Case I: Centralized management for LES: Fig. 6 and Fig. 7 show the electricity and heat balance for LES while the MEP manages all facilities centrally. The IL is not used, so the demand is unchanged during the day. As it is shown, the main production of CHP units occurs during hours 9-13 and 17-21, when the electricity wholesale price is maximum and the MED have simultaneous consumption of electricity and heat. It should be noted that most of the time the CHP units are in heat-following mode and produce electricity based on their heat demand and just at hours 22 and 23 the CHP units are in electricity-following mode. In these hours the electricity price is very high, but LES #1 doesn't have enough heat demand, therefore the surplus heat production of CHP #1 stored in HS #1 and CHP #1 can operate in electricity-following mode. Moreover, at hours 9-12 the MEP can inject its electricity generation to the upstream network, when the electricity price is almost high. At these hours, the renewable energy generation is maximum and the high heat demand leads to the minimum

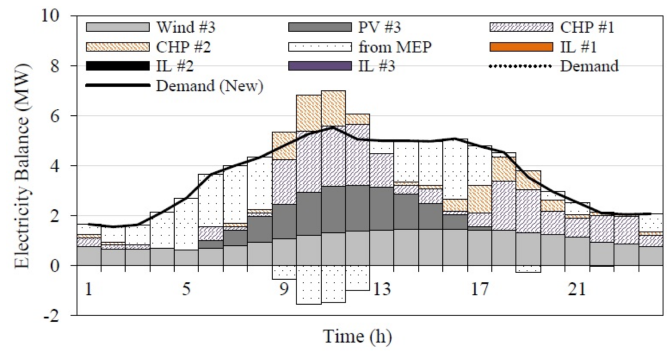

Fig. 6: Share of each element in electricity balance of LES in Case I.

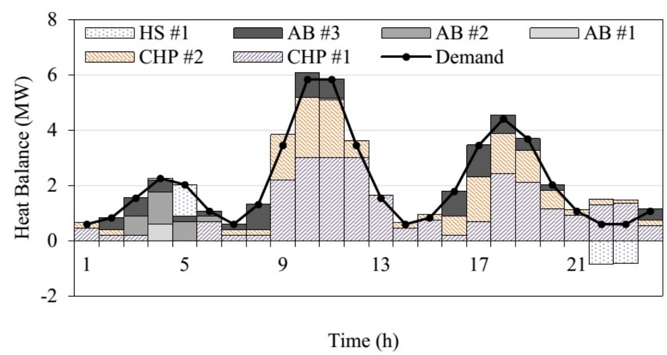

Fig. 7: Share of each element in heat energy balance of LES in Case I.

marginal cost for the CHP units. Therefore, the total marginal cost for electricity production of the MEP will be lower than the wholesale electricity market price.

2) Case II: Direct pricing mode: In this mode, the MEP determines the energy prices to interact with each LES. After that, each LES schedules its heat and electricity balance. Fig. 8 reports the equilibrium price for the electricity, gas, and heat carriers in each LES. Moreover, Fig. 9 and Fig. 10 show the electricity and heat balance for LES, respectively. As it is shown, the MEP determines different energy prices for each LES to maximize its profit by changing the behavior of each LES, independently. The MEP is the only supplier of natural gas in the system; therefore, the MEP increases the gas price up to the price cap to maximize its profit. Moreover, high gas price leads to increase the marginal cost of the CHP units' electricity production.

For LES #1 (that can satisfy its heat demand from HS, AB, and CHP) the MEP maintains the heat price to the lowest amount, to prevent heat injection of LES #1 to other LES. Moreover, the equilibrium heat price is based on the marginal cost of heat production in LES.

The electricity price for each LES is related to the flexibility of LES to change its energy interaction with the MEP. For LES #1 that has an efficient CHP unit, the electricity equilibrium price is almost equal to the marginal cost of the CHP unit. Only at hour 11, when the price of the electricity wholesale market is high, the MEP increases the equilibrium price to the price cap, to motivate LES #1 to increase its CHP units'

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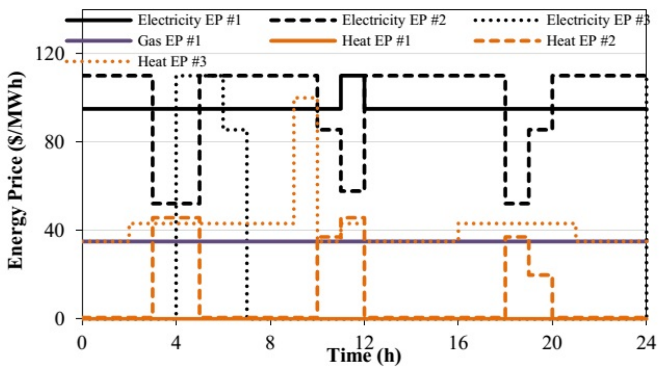

Fig. 8: Electricity equilibrium price between MEP and LES in Case II.

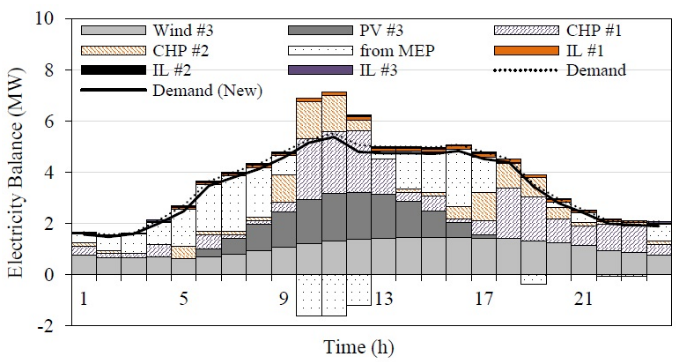

Fig. 9: Share of each element in electricity balance of LES in Case II.

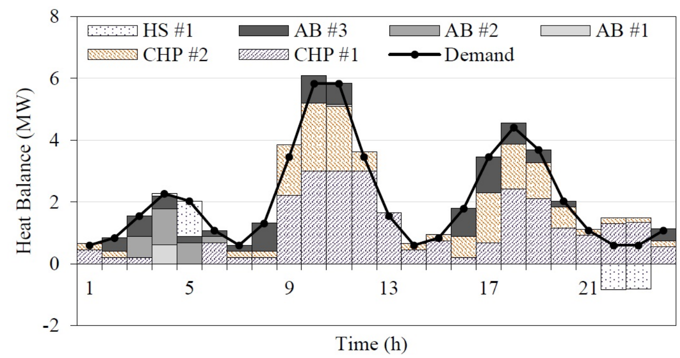

Fig. 10: Share of each element in heat energy balance of LES in Case II.

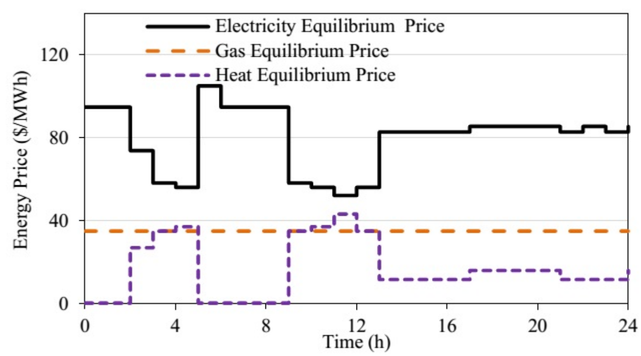

Fig. 11: Electricity equilibrium price between MEP and LES in Case III.

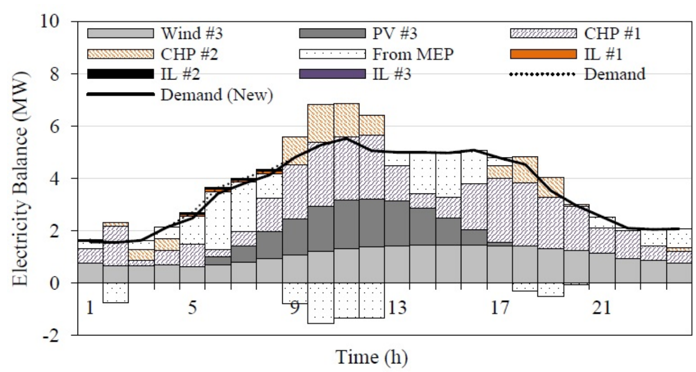

Fig. 12: Share of each element in electricity energy balance of LES in Case III.

production to its maximum level. For LES #2, the efficiency of the CHP unit is lower; therefore, the marginal cost of the CHP unit production is low, while the LES #2 has maximum heat demand. Therefore, during the peak of heat demand in LES #2, the marginal cost of electricity production for LES #2 decreases, and consequently the electricity equilibrium price is decreased, dramatically. For LES #3 with high penetration of renewable energy, the marginal cost of electricity generation is very low; therefore, at most of the hours the electricity equilibrium price is at the lowest amount for LES #3. During hours 4-6, while the renewable energy generation is very low and LES #3 has no more option to generate electricity, the MEP increases the electricity price up to the price cap to maximize its profit from selling energy to LES #3. It should be noted that in this mode the LES utilize their IL resources at the maximum level. This happens because the MEP enforces different prices for each LES, and the average electricity price is higher than in the other cases.

3) Case III: Uniform pricing for LES: In this mode all LES schedule their energy balance based on the same equilibrium price. Fig. 11 shows the equilibrium price for the electricity, heat, and gas carriers. Fig. 12 and Fig. 13 show the electricity and heat balances, respectively. Due to the same price for all LES in this case, the equilibrium is formed from all LES and has more variation. Similarly to Case II, the MEP is the only supplier of natural gas, and increases the gas price up to the price cap. The MEP aims to maximize its profit and has three main strategies to impact on the LES behavior:

- In the first strategy (e.g. hours 3, 4, and 13-16) the MEP decreases the energy price to the marginal cost of CHP units to increase its market share and total profit.
- In the second strategy (e.g. hours 9-12), the MEP decreases the energy price and injects LES surplus energy to the upstream network to maximize its profit. In these hours, due to high heat consumption and high renewable energy production, the marginal cost of electricity production for LES is low. Therefore, the MEP can buy electricity at lower price from LES and sell it to the

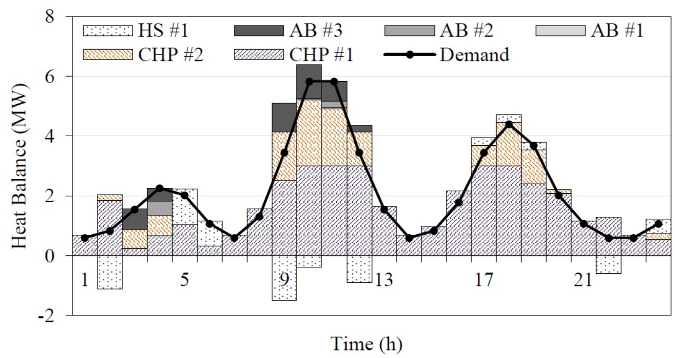

Fig. 13: Share of each element in heat energy balance of LES in Case III.

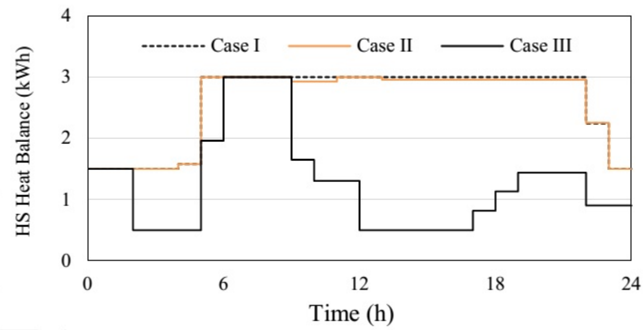

Fig. 14: Comparison of HS unit operation in Case I, II, and III

TABLE II: DATA OF $LRUF$ INDEXES.

	$LRUF_e$	$LRUF_h$
Centralized	0.272	0.254
Direct Pricing	0.272	0.255
Uniform Pricing	0.302	0.342

electricity market.

- In the third strategy (e.g. hours 5-8), the MEP increases the equilibrium price to maximize its profit through selling the remaining LES energy at the maximum price.

It should be noted that the profit of the MEP is related to the energy content that the MEP interacts with other energy players. For instance, in the case during hours 9-12, the MEP buys electricity from LES at higher price than from the electricity market, and sells it to the electricity market. The key point is that the LES generate electricity by utilizing CHP units, and CHP units consume natural gas as primary resources. Therefore, by generating more electricity by using CHP units it means that the MEP sells more natural gas to the LES. Therefore, the net energy content that the MEP is interacting with the electricity wholesale market and LES is profitable.

C. Effectiveness Assessment Based on Decision Making Framework

Table II shows the amount of each system effectiveness indexes for three energy interaction conditions. The LES have two output to the MED, therefore, the $LRUF$ index from (47) has been calculated for both heat and electricity, i.e., the carrier $c = \{e,\ h\}$. As it is shown, the difference between centralized management mode and direct pricing is negligible in both cases. In the centralized management mode, the MEP can control all facilities of LES directly; in the same way as in the direct pricing mode, the MEP sends price signals to each LES, individually and can change the behavior of LES. Although the mechanisms to shape the behavior of LES in these two modes are different, the final behavior of LES and especially the energy interactions among LES and MEP are the same.

In the uniform pricing mode, the system effectiveness index is higher than in the two other modes for each energy carrier. From the direct to the uniform pricing mode, the $LRUF$ index for heat shows 11% increase, and for electricity it shows 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 utilize their internal energy resources for both electricity and heat. The sharp increase in $LRUF_h$ is due to more utilization of CHP and HS units in uniform pricing, compared with the direct pricing mode. Fig. 14 shows the operational behavior of HS during 24 hours. In this figure the HS has more variation in case III when the MEP interacts energy in uniform pricing mode. It shows more operational flexibility of LES in the uniform pricing mode.

D. Effectiveness Assessment Based on Local Players Characteristics

This section shows the results of the proposed approach with a growing number of LES. Without loss of generality, the results obtained from Case III (uniform pricing) with three LES are taken as the starting point. The number of LES is then increased in order to create three energy mix types, namely:

- Type I: only the number of LES #1 is increased
- Type II: only the number of LES #2 is increased
- Type III: only the number of LES #3 is increased

The added LES for each type have the same characteristics, but are included in the model in an independent way, thus increasing the dimensions of the vectors and matrices used.

The impact of the different types of energy mix on the flexibility of LES to use the internal energy resources for electricity and heat is expressed through the indexes $LRUF_e$ and $LRUF_h$.

By increasing the amount of LES #1 in Type I energy mix, higher production marginal costs appear. Thereby, the utilization factor of CHP units decreases, the HS capacity in the system increases, and the system experiences a reduction in both indexes $LRUF_e$ (Fig. 15) and $LRUF_h$ (Fig. 16).

From Fig. 15, the index $LRUF_e$ increases by increasing the number of LES of Type II and Type III. In fact, increasing the number of LES, the lower production marginal cost leads to increasing the utilization of electricity-based LES (for Type II) and renewable-based LES (for Type III).

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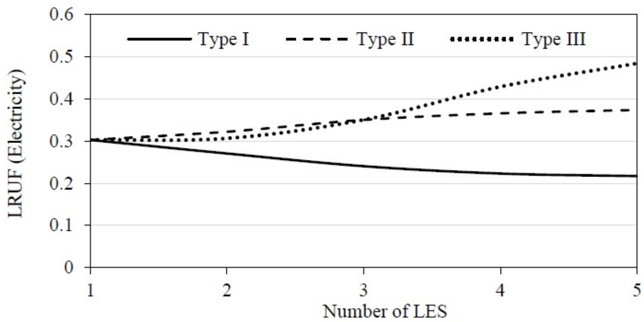

Fig. 15: $LRUF_e$ amount for three types of LES.

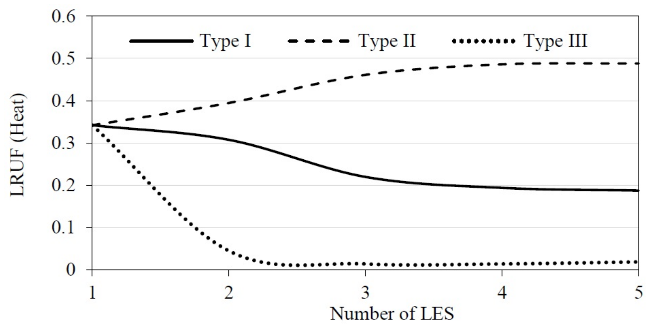

Fig. 16: $LRUF_h$ amount for three types of LES.

From Fig. 16, the index $LRUF_h$ increases by increasing the number of LES of Type II. In this condition, the share of CHP units in electricity generation increases, heat is produced as supplementary energy carrier from CHP units, and the HS usage becomes higher. The rate of $LRUF_h$ increase is gradually reduced for higher numbers of LES. On the contrary, by increasing the number of LES of Type III, higher shares of renewable resources impact on the operation of the CHP units and lead to a significant reduction in the $LRUF_h$ index.

The computation time of the solutions indicated in Fig. 15 and Fig. 16 ranges from approximately one minute for the starting point, up to 15 minutes for the case with 5 LES of Type I that is equipped by energy storage unit. For types II and III the increase of computation time versus the number of LES is more linear and for the case with 5 LES is approximately 5 minutes. The use of parallel processors to run the calculations on the individual LES would decrease the computation time.

VI. Conclusion

This paper has developed a model of MEP cooperation in multi-energy systems. Firstly, a hierarchical structure has been proposed to represent the MEP energy exchange with LES. After that, the MEP and LES have been modeled, independently. The decision-making conflicts among these players have been modeled through an MINLP bi-level approach. At the upper level, the MEP aims to maximize its profit and the equilibrium prices are determined by cooperation of all LES. At 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 with its KKT optimality conditions. After that, based on the strong duality theorem, the objective function of the upper level problem has been linearized.

The key findings from the numerical results are as follows:

- The resource allocation of each LES determines its operational flexibility in the short term and explains its behavior to cooperate with other LES in a multi-energy system.
- The presence of appropriate energy interaction conditions in multi-energy systems affects the MEP behavior and makes it possible to exploit synergies among LES.
- For local energy carriers that produce and consume locally (i.e., heat), the variable marginal price motivates the MEP to utilize its internal resources for maximizing its profit.
- Main energy carriers that cannot be generated locally (i.e., gas) should be regulated appropriately to mitigate the energy price spike in the local network.
- The proposed approach may be applied to planning studies aimed at showing the impact of increasing a certain type of LES on the effectiveness indexes.
- Due to linear mathematical modeling, the proposed approach guarantees to reach the global optimum. The computational burden can be reduced by utilizing parallel processors to run the individual LES optimizations.

In the future works, the role of MEP in energy market environment will be further investigated, by evaluating the economic functions of the energy market based on the penetration rate of the MEP.

Appendix A
Modeling of the Renewable Energy Resource Uncertainty

The uncertainty in the inputs from renewable energy sources (wind generation and PV arrays, in this study) is modeled by generating appropriate scenarios for the study. For this purpose, time-series based models such as ARIMA, or artificial intelligence models (e.g., neural networks, data mining, and evolutionary computation) can be used. In this paper, the same approach is used for PV and wind. The full description of the procedure is explained for the case of wind power.

Wind speed distributions are often characterized by Weibull distributions [29]. The Probability Density Function (PDF) of the wind speed is represented by (49), where $c > 0$ and $k > 0$ are the scale factor and the shape factor, respectively.

$$f_v(v) = \frac{k}{c}\left(\frac{v}{c}\right)^{k-1} exp\left[-\left(\frac{v}{c}\right)^{k}\right] \quad (49)$$

The probability distribution function is divided into N_s scenarios, and the probability of each step can be calculated as follows:

$$prob_\omega = \int_{WS_\omega}^{WS_{\omega+1}} f_v(v)\ dv, \qquad \omega = 1, 2, ..., N_s \quad (50)$$

where WS_ω is the wind speed of the ω^{th} scenario. The power generated, $P_{GW}(\omega)$, corresponding to a specific wind

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/TSTE.2017.2701836, IEEE Transactions on Sustainable Energy

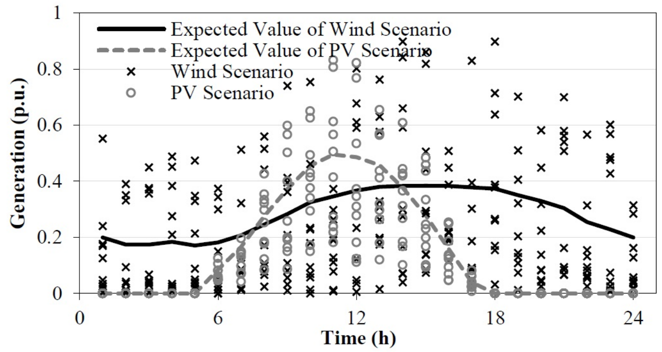

Fig. 17: PV and Wind Scenarios for LES III in p.u.

speed WS_ω can be obtained from (50) in which A, B, and C are constants calculated according with [29].

$$P_{GW}(\omega) = \begin{cases} 0 & 0 \leq WS_\omega \leq V_c \text{ or } WS_\omega \geq V_{c0} \\ P_r(A + B * WS_\omega + C * WS_\omega^2) & V_c \leq WS_\omega \leq V_r \\ P_r & V_r \leq WS_\omega \leq V_{c0} \end{cases} \tag{51}$$

In (51), V_c, V_{c0}, and V_{cr} represent cut-in speed, cut-out speed, and rated speed, respectively. Different realizations of wind power generation are modeled through a scenario generation process based on the Roulette Wheel Mechanism (RWM) [30]. At first, the distribution function is divided into some class intervals. Moreover, each interval is associated with a probability. Subsequently, according to different intervals and their probabilities obtained by PDF, the RWM is applied to generate scenarios for each hour. To this end, at first, the probabilities of different intervals are normalized in a way that their summation becomes equal to unity. After that, random numbers are generated between 0 and 1. Each random number falls in the normalized probability range of a wind power generation interval in the roulette wheel. That wind power generation interval is selected by the roulette wheel mechanism for the respective scenario. Of course, higher numbers of scenarios produce a more accurate model to consider the mentioned uncertainties. However, it yields an unmanageable optimization problem. Hence, a scenario reduction technique is considered, using the K-means clustering technique [31], resulting in a scenario tree with ten independent scenarios, used in case studies. In this paper, the Swift Current wind data are used to generate wind power scenarios [32]. The final utilized scenarios for PV and wind generation and the expected values are depicted in Fig. 17.

APPENDIX B
COMPREHENSIVE MPEC MODELING

The MPEC formulation of problem as follows:
Linear Objective Function:

$$\max \Bigg\{ \sum_t \Bigg[-(w_t^{MEP}\Pi_{e,t}^{EM} + g_t^{MEP}\Pi_{g,t}^{GM})$$

$$+ \sum_i \Bigg((W_{i,t}^{MED} - w_{i,t}^{IL})\Pi_{e,i,t}^{MED} + G_{i,t}^{MED}\Pi_{g,i,t}^{MED}$$

$$+ Q_{i,t}^{MED}\Pi_{h,i,t}^{MED} - w_{i,t}^{IL}\Pi_{i,t}^{IL,inc} \Bigg)$$

$$+ \lambda_{e,i,t}^{MED} W_{i,t}^{MED} + \lambda_{g,i,t}^{MED} G_{i,t}^{MED} + \lambda_{h,i,t}^{MED} Q_{i,t}^{MED}$$

$$-0.5\lambda_{h,i,\omega,t}^{HS} Q_{i,\omega,t}^{HS}\Big|_{t=1} + \xi_{h,i,\omega,t}^{HS}\Big|_{t=1} Q_{i,\omega,t}^{HS}/2$$

$$+ \xi_{h,i,\omega,t}^{HS}\Big|_{t=T} Q_{i,\omega,t}^{HS}/2 - \overline{\mu}_{e,i,\omega,t}^{LES,in}\overline{W}_i^{LES} - \overline{\mu}_{e,i,\omega,t}^{LES,out}\overline{W}_i^{LES}$$

$$-\overline{\mu}_{h,i,\omega,t}^{LES,in}\overline{Q}_i^{LES} - \overline{\mu}_{h,i,\omega,t}^{LES,out}\overline{Q}_i^{LES} - \overline{\mu}_{g,i,\omega,t}^{LES}\overline{G}_i^{LES}$$

$$-\overline{\mu}_{e,i,\omega,t}^{CHP}\overline{W}_i^{CHP} - \overline{\mu}_{h,i,\omega,t}^{CHP}\overline{Q}_i^{CHP} - \overline{\mu}_{h,i,\omega,t}^{AB}\overline{Q}_i^{AB}$$

$$-\overline{\mu}_{h,i,\omega,t}^{HS,in}\gamma_i^{HS} - \overline{\mu}_{h,i,\omega,t}^{HS,out}\gamma_i^{HS} - \overline{\mu}_{h,i,\omega,t}^{HS}\overline{Q}_i^{HS}$$

$$-\overline{\mu}_{e,i,\omega,t}^{PV}\overline{W}_i^{PV,Forecast} - \overline{\mu}_{e,i,\omega,t}^{Wind}\overline{W}_i^{Wind,Forecast}$$

$$-\overline{\mu}_{e,i,\omega,t}^{IL}\alpha_{i,t}^{IL}W_{i,t}^{MED} \Bigg]\Bigg\} \tag{52}$$

Primal Optimality Conditions:

$$\overline{W}^{MEP} \leq w_t^{MEP} \leq \underline{W}^{MEP} \tag{53}$$

$$0 \leq g_t^{MEP} \leq \underline{G}^{MEP} \tag{54}$$

$$w_t^{MEP} - \sum_i \hat{w}_{i,t}^{LES} = 0 \tag{55}$$

$$g_t^{MEP} - \sum_i \hat{g}_{i,t}^{LES} = 0 \tag{56}$$

$$\sum_i \hat{q}_{i,t}^{LES} = 0 \tag{57}$$

Stationary Conditions:

$$\partial\mathcal{L}_i^{LES}/\partial w_{i,\omega,t}^{LES,in} = \pi_{e,i,t}^{MEP} - \lambda_{e,i,t}^{MED}\eta_{e,i}^{Trans} - \underline{\mu}_{e,i,\omega,t}^{LES,in} + \overline{\mu}_{e,i,\omega,t}^{LES,in} = 0 \tag{58}$$

$$\partial\mathcal{L}_i^{LES}/\partial w_{i,\omega,t}^{LES,out} = -\pi_{e,i,t}^{MEP} + \lambda_{e,i,t}^{MED}/\eta_{e,i}^{Trans} - \underline{\mu}_{e,i,\omega,t}^{LES,out} + \overline{\mu}_{e,i,\omega,t}^{LES,out} = 0 \tag{59}$$

$$\partial\mathcal{L}_i^{LES}/\partial g_{i,\omega,t}^{LES} = \pi_{g,i,t}^{MEP} - \lambda_{e,i,t}^{MED} - \underline{\mu}_{g,i,\omega,t}^{LES} + \overline{\mu}_{g,i,\omega,t}^{LES} = 0 \tag{60}$$

$$\partial\mathcal{L}_i^{LES}/\partial q_{i,\omega,t}^{LES,in} = \pi_{h,i,t}^{MEP} - \lambda_{h,i,t}^{MED}\eta_{h,i}^{LES} - \underline{\mu}_{h,i,\omega,t}^{LES,in} + \overline{\mu}_{h,i,\omega,t}^{LES,in} = 0 \tag{61}$$

$$\partial\mathcal{L}_i^{LES}/\partial q_{i,\omega,t}^{LES,out} = \pi_{h,i,t}^{MEP} + \lambda_{h,i,t}^{MED}/\eta_{h,i}^{LES} - \underline{\mu}_{h,i,\omega,t}^{LES,out} + \overline{\mu}_{h,i,\omega,t}^{LES,out} = 0 \tag{62}$$

$$\partial\mathcal{L}_i^{LES}/\partial w_{i,\omega,t}^{CHP} = -\lambda_{e,i,t}^{MED} + \lambda_{e,i,\omega,t}^{CHP} + \lambda_{i,\omega,t}^{Ratio}\Phi_i^{CHP} - \underline{\mu}_{e,i,\omega,t}^{CHP} + \overline{\mu}_{e,i,\omega,t}^{CHP} = 0 \tag{63}$$

$$\partial\mathcal{L}_i^{LES}/\partial q_{i,\omega,t}^{CHP} = -\lambda_{h,i,t}^{MED} + \lambda_{h,i,\omega,t}^{CHP} - \lambda_{i,\omega,t}^{Ratio} - \underline{\mu}_{h,i,\omega,t}^{CHP} + \overline{\mu}_{h,i,\omega,t}^{CHP} = 0 \tag{64}$$

$$\partial\mathcal{L}_i^{LES}/\partial g_{i,\omega,t}^{CHP} = \lambda_{g,i,t}^{MED} - \lambda_{e,i,\omega,t}^{CHP}\eta_{e,i}^{CHP} - \lambda_{h,i,\omega,t}^{CHP}\eta_{h,i}^{CHP} = 0 \tag{65}$$

$$\partial\mathcal{L}_i^{LES}/\partial q_{i,\omega,t}^{AB} = -\lambda_{h,i,t}^{MED} + \lambda_{h,i,\omega,t}^{AB} - \underline{\mu}_{h,i,\omega,t}^{AB} + \overline{\mu}_{h,i,\omega,t}^{AB} = 0 \tag{66}$$

$$\partial\mathcal{L}_i^{LES}/\partial g_{i,\omega,t}^{AB} = \lambda_{g,i,t}^{MED} - \lambda_{h,i,\omega,t}^{AB}\eta_{h,i}^{AB} = 0 \tag{67}$$

$$\partial\mathcal{L}_i^{LES}/\partial q_{i,\omega,t}^{HS,in} = \lambda_{h,i,t}^{MED} + \lambda_{h,i,\omega,t}^{HS}\eta_{h,i}^{HS} - \underline{\mu}_{h,i,\omega,t}^{HS,in} + \overline{\mu}_{h,i,\omega,t}^{HS,in} = 0 \tag{68}$$

$$\partial\mathcal{L}_i^{LES}/\partial q_{i,\omega,t}^{HS,out} = -\lambda_{h,i,t}^{MED} - \lambda_{h,i,\omega,t}^{HS}/\eta_{h,i}^{HS} - \underline{\mu}_{h,i,\omega,t}^{HS,out} + \overline{\mu}_{h,i,\omega,t}^{HS,out} = 0 \quad (69)$$

$$\partial\mathcal{L}_i^{LES}/\partial q_{i,\omega,t}^{HS} = \lambda_{h,i,\omega,t}^{HS} - \lambda_{h,i,\omega,t+1}^{HS} - \underline{\mu}_{h,i,\omega,t}^{HS} + \overline{\mu}_{h,i,\omega,t}^{HS} = 0 \quad (70)$$

$$\partial\mathcal{L}_i^{LES}/\partial w_{i,\omega,t}^{Wind} = -\lambda_{e,i,t}^{MED} - \underline{\mu}_{e,i,\omega,t}^{Wind} + \overline{\mu}_{e,i,\omega,t}^{Wind} = 0 \quad (71)$$

$$\partial\mathcal{L}_i^{LES}/\partial w_{i,\omega,t}^{PV} = -\lambda_{e,i,t}^{MED} - \underline{\mu}_{e,i,\omega,t}^{PV} + \overline{\mu}_{e,i,\omega,t}^{PV} = 0 \quad (72)$$

$$\partial\mathcal{L}_i^{LES}/\partial w_{i,\omega,t}^{IL} = -\lambda_{e,i,t}^{MED} - \underline{\mu}_{e,i,\omega,t}^{IL} + \overline{\mu}_{e,i,\omega,t}^{IL} = 0 \quad (73)$$

Complementary Conditions:

$$0 \leqslant \underline{\mu}_{e,i,\omega,t}^{LES,in} \perp (w_{i,\omega,t}^{LES,in}) \geqslant 0 \quad (74)$$

$$0 \leqslant \overline{\mu}_{e,i,\omega,t}^{LES,in} \perp (\overline{W}_i^{LES} - w_{i,\omega,t}^{LES,in}) \geqslant 0 \quad (75)$$

$$0 \leqslant \underline{\mu}_{e,i,\omega,t}^{LES,out} \perp (w_{i,\omega,t}^{LES,out}) \geqslant 0 \quad (76)$$

$$0 \leqslant \overline{\mu}_{e,i,\omega,t}^{LES,out} \perp (\overline{W}_i^{LES} - w_{i,\omega,t}^{LES,out}) \geqslant 0 \quad (77)$$

$$0 \leqslant \underline{\mu}_{h,i,\omega,t}^{LES,in} \perp (q_{i,\omega,t}^{LES,in}) \geqslant 0 \quad (78)$$

$$0 \leqslant \overline{\mu}_{h,i,\omega,t}^{LES,in} \perp (\overline{Q}_i^{LES} - q_{i,\omega,t}^{LES,in}) \geqslant 0 \quad (79)$$

$$0 \leqslant \underline{\mu}_{h,i,\omega,t}^{LES,out} \perp (q_{i,\omega,t}^{LES,out}) \geqslant 0 \quad (80)$$

$$0 \leqslant \overline{\mu}_{h,i,\omega,t}^{LES,out} \perp (\overline{Q}_i^{LES} - q_{i,\omega,t}^{LES,out}) \geqslant 0 \quad (81)$$

$$0 \leqslant \underline{\mu}_{g,i,\omega,t}^{LES} \perp (g_{i,\omega,t}^{LES}) \geqslant 0 \quad (82)$$

$$0 \leqslant \overline{\mu}_{g,i,\omega,t}^{LES} \perp (\overline{G}_i^{LES} - g_{i,\omega,t}^{LES}) \geqslant 0 \quad (83)$$

$$0 \leqslant \underline{\mu}_{e,i,\omega,t}^{CHP} \perp (w_{i,\omega,t}^{CHP}) \geqslant 0 \quad (84)$$

$$0 \leqslant \overline{\mu}_{e,i,\omega,t}^{CHP} \perp (\overline{W}_i^{CHP} - w_{i,\omega,t}^{CHP}) \geqslant 0 \quad (85)$$

$$0 \leqslant \underline{\mu}_{h,i,\omega,t}^{CHP} \perp (q_{i,\omega,t}^{CHP}) \geqslant 0 \quad (86)$$

$$0 \leqslant \overline{\mu}_{h,i,\omega,t}^{CHP} \perp (\overline{Q}_i^{CHP} - q_{i,\omega,t}^{CHP}) \geqslant 0 \quad (87)$$

$$0 \leqslant \underline{\mu}_{h,i,\omega,t}^{AB} \perp (q_{i,\omega,t}^{AB}) \geqslant 0 \quad (88)$$

$$0 \leqslant \overline{\mu}_{h,i,\omega,t}^{AB} \perp (\overline{Q}_i^{AB} - q_{i,\omega,t}^{AB}) \geqslant 0 \quad (89)$$

$$0 \leqslant \underline{\mu}_{h,i,\omega,t}^{HS,in} \perp (q_{i,\omega,t}^{HS,in}) \geqslant 0 \quad (90)$$

$$0 \leqslant \overline{\mu}_{h,i,\omega,t}^{HS,in} \perp (\gamma_i^{HS} - q_{i,\omega,t}^{HS,in}) \geqslant 0 \quad (91)$$

$$0 \leqslant \underline{\mu}_{h,i,\omega,t}^{HS,out} \perp (q_{i,\omega,t}^{HS,out}) \geqslant 0 \quad (92)$$

$$0 \leqslant \overline{\mu}_{h,i,\omega,t}^{HS,out} \perp (\gamma_i^{HS} - q_{i,\omega,t}^{HS,out}) \geqslant 0 \quad (93)$$

$$0 \leqslant \underline{\mu}_{h,i,\omega,t}^{HS} \perp (q_{i,\omega,t}^{HS}) \geqslant 0 \quad (94)$$

$$0 \leqslant \overline{\mu}_{h,i,\omega,t}^{HS} \perp (\overline{Q}_i^{HS} - q_{i,\omega,t}^{HS}) \geqslant 0 \quad (95)$$

$$0 \leqslant \underline{\mu}_{e,i,\omega,t}^{PV} \perp (w_{i,\omega,t}^{PV}) \geqslant 0 \quad (96)$$

$$0 \leqslant \overline{\mu}_{e,i,\omega,t}^{PV} \perp (\overline{W}_i^{PV,Forecast} - w_{i,\omega,t}^{PV}) \geqslant 0 \quad (97)$$

$$0 \leqslant \underline{\mu}_{e,i,\omega,t}^{Wind} \perp (w_{i,\omega,t}^{Wind}) \geqslant 0 \quad (98)$$

$$0 \leqslant \overline{\mu}_{e,i,\omega,t}^{Wind} \perp (\overline{W}_i^{Wind,Forecast} - w_{i,\omega,t}^{Wind}) \geqslant 0 \quad (99)$$

$$0 \leqslant \underline{\mu}_{e,i,\omega,t}^{IL} \perp (w_{i,\omega,t}^{IL}) \geqslant 0 \quad (100)$$

$$0 \leqslant \overline{\mu}_{e,i,\omega,t}^{IL} \perp (\alpha_{i,t}^{IL} W_{i,t}^{MED} - w_{i,\omega,t}^{IL}) \geqslant 0 \quad (101)$$

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